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VOLUME 4
S-W, Index

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Volume 4 S-W, Index

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ENCYCLOPEDIA OF Agricultural Science

Volume 4 S-W, Index

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Academic Press
San Diego New York Boston London Sydney Tokyo Toronto

This book is printed on acid-free paper. ∞

Academic Press, Inc.
A Division of Harcourt Brace & Company
525 B Street, Suite 1900, San Diego, California 92101-4495

United Kingdom Edition published by
Academic Press Limited
24-28 Oval Road, London NW1 7DX

Library of Congress Cataloging-in-Publication Data

Encyclopedia of agricultural science / edited by Charles J. Arntzen, Ellen M. Ritter.
p. cm.
Includes index.
ISBN 0-12-226670-6 (set) -- ISBN 0-12-226671-4 (v. 1)
ISBN 0-12-226672-2 (v. 2) -- ISBN 0-12-226673-0 (v. 3)
ISBN 0-12-226674-9 (v. 4)
1. Agriculture--Encyclopedias. I. Arntzen, Charles J. II. Ritter, Ellen M.
S411.E713 1994
630'.3--dc20 94-3143
CIP

PRINTED IN THE UNITED STATES OF AMERICA
94 95 96 97 98 99 QW 9 8 7 6 5 4 3 2 1

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HOW TO USE THE ENCYCLOPEDIA

The *Encyclopedia of Agricultural Science* is intended for use by both students and research professionals. Articles have been chosen to reflect major disciplines in the study of agricultural science, common topics of research by professionals in this realm, areas of public interest and concern, and areas of economics and policy. Each article thus serves as a comprehensive overview of a given area, providing both breadth of coverage for students and depth of coverage for research professionals. We have designed the *Encyclopedia* with the following features for maximum accessibility for all readers.

Articles in the *Encyclopedia* are arranged alphabetically by subject. A complete table of contents appears in each volume. Here, one will find broad discipline-related titles such as "Agroforestry" and "Plant Pathology," research topics such as "Transgenic Animals" and "Photosynthesis," areas of public interest and concern such as "Plant Biotechnology: Food Safety and Environmental Issues" and "World Hunger and Food Security," and areas of economics and policy such as "Macroeconomics of World Agriculture" and "Consultative Group on International Agricultural Research."

Each article contains an outline, a glossary, cross references, and a bibliography. The outline allows a quick scan of the major areas discussed within each article. The glossary contains terms that may be unfamiliar to the reader, with each term defined in the context of its use in that article. Thus, a term may appear in the glossary for another article defined in a slightly different manner or with a subtle nuance specific to that article. For clarity, we have allowed these differences in definition to remain so that the terms are defined relative to the context of each article.

Each article has been cross referenced to other articles in the *Encyclopedia*. Cross references are found at the end of the paragraph containing the first mention of a subject area covered elsewhere in the *Encyclopedia*. We encourage readers to use the cross references to locate other encyclopedia articles that will provide more detailed information about a subject. These cross references are also identified in the Index of Related Titles, which appears in Volume 4.

The bibliography lists recent secondary sources to aid the reader in locating more detailed or technical information. Review articles and research articles that are considered of primary importance to the understanding of a given subject area are also listed. Bibliographies are not intended to provide a full reference listing of all material covered in the context of a given article, but are provided as guides to further reading.

Two appendices appear in Volume 4. Appendix A lists United States colleges and universities granting degrees in agriculture. Appendix B lists United Nations organizations concerned with agriculture and related issues. Both appendices provide address and telephone information for each institution listed.

The Subject Index is located in Volume 4. Because the reader's topic of interest may be listed under a broader article title, we encourage use of the index for access to a subject area. Entries appear with the source volume number in boldface followed by a colon and the page number in that volume where the information occurs.

S

Silk Production and Processing

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Glossary

Fibroin Structural peptide in silk that forms a highly crystalline β sheet and imparts mechanical strength to the fiber

Sericin A family of gummy peptides in silk that bind the fibroin chains together to form the silk fiber

Silk Spun fibrous protein polymer secretions produced by biological systems which usually form an external structure (e.g., cocoon, web)

Silks are generally defined as spun fibrous protein polymer secretions produced by biological systems. Silks are synthesized by a variety of organisms including silkworms (and most other Lepidoptera larvae), spiders, scorpions, mites, and flies. The structure and function of silk fibers depend on the organism producing the silk. Silkworm silks have been the most intensively studied and are synthesized in specialized sets of modified salivary glands and extruded from spinnerets located in the head of the larva. The majority of silks are spun into air, although some aquatic insects produce silks with differing compositions that are spun under water.

I. General Characteristics of Silk

The most well-characterized silk is that produced by the domesticated silkworm, *Bombyx mori*. Sericulture is the agricultural practice of growing mulberry (primary food for the silkworms), raising silkworms for silk production, harvesting silk from cocoons, and processing of the cocoon silk into useful textile fibers. The practice of sericulture originated in China nearly 5000 years ago and since that time silk has been used in textiles. Silkworm silk is produced primarily at one stage in the life cycle, during the fifth larval instar just before molt to the pupa. Smaller quantities of silk are produced at all larval stages except during molts. The silkworm cocoon is composed of silk fibroin, the structural fibers of the silk, and sericins, a family of gummy proteins that bind the fibers together. The cocoon is essentially a composite structure of fibroin fibers embedded in a sericin matrix to provide the insect with a protective sheath from the environment. The silk from each cocoon comprises a single thread ranging between 10 and 25 μm in diameter and between 300 and 1200 m in length. Silks are of interest in textiles and other material applications due to their visual appearance, their texture (or "feel"), their environmental stability, and their unique mechanical properties.

II. Silk Production in Silkworm

A. Life Cycle

The life cycle of *B. mori* is summarized in Fig. 1. The silkworm is a holometabolous insect. In about 50 days it completes its life cycle of four different metamorphosizing phases; egg or embryo, larva, pupa, and adult (moth). When over-wintered eggs are kept at natural temperatures, the larvae hatch in April or May in response to an increase in temperature. Of the life cycle, about half is the larval stage, the only stage at which they consume food, mulberry leaves. Although silk protein is produced throughout the larval stages, except during molting, large amounts are syn-

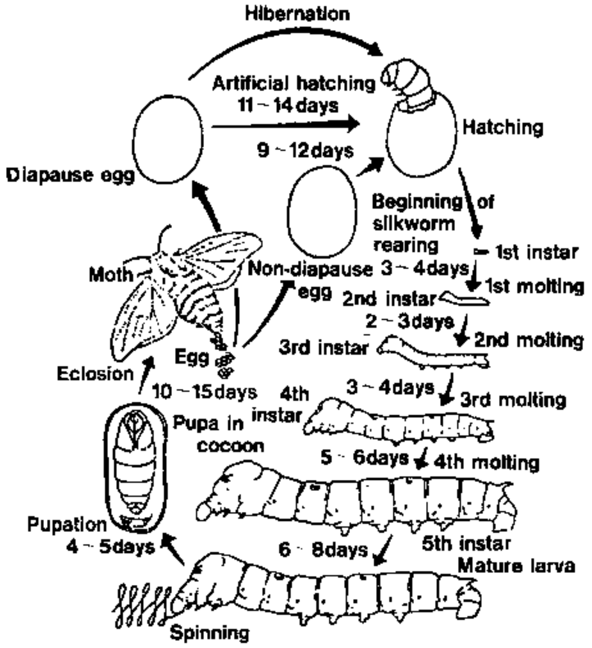


FIGURE 1 Life cycle of *Bombyx mori*. [Reprint with permission from Asakura, T. *JEOL News* **23A** (2), 1987.]

thesized in fifth instar larval stage. Pupation occurs at the end of spinning (or cocoon formation); the latter takes 3–4 days. This spinning stage is characterized by the extrusion of silk from spinnerets located in the head and drawing of the fiber by a characteristic figure-eight head movement. Inside the cocoon, the larva pupates. The moth emerges after a 10- to 15-day period of adult development. Mating occurs soon after emergence and 300–600 eggs are laid immediately afterward.

The duration of the developmental stages can be controlled throughout the life cycle by regulating environmental conditions, mainly temperature and nutrition. The developmental character of the early embryo, either diapausing or nondiapausing, can also be controlled by conditioning the female with temperature and photoperiod cycling during the egg incubation period and early larval stages. Furthermore, even the date of hatching can be scheduled by applying artificial hatching treatments in combination with cold storage. [*See* INSECT PHYSIOLOGY.]

B. Synthesis of Silk Protein

After the fourth larval molt or ecdysis, the silk gland of the silkworm develops rapidly for active fibroin production, and in the fifth instar larva it is the second largest organ following the alimentary canal. The gland in which the silk of *B. mori* is secreted is shown in Fig.2. This consists of three relatively distinct regions. Fibroin, the main component of silk proteins, is exclusively synthesized in the posterior region of the silk gland and is transferred by peristalsis into the middle region of the gland in which it is stored as a very viscous aqueous solution until required for spinning. In the walls of the middle region of the gland, another silk protein, sericin is produced which coats the silk fibroin, acting as an adhesive; both proteins have unique and easily distinguishable amino acid compositions (Table I). The two glands join together immediately before the spinnerets through the anterior region and the fiber is spun into air. In the extruded thread, the two fibroin cores remain distinct. The silk gland is considered to be an ideal model system for producing large amounts of specialized proteins. Recently, an *in vitro* silk fibroin production system has been developed by the culture of the posterior region of the silk gland from *B. mori*.

C. Silkworm Nutrition

B. mori feeds almost exclusively on mulberry leaves (or close botanical relatives) because of the need for chemo-attractants and feeding stimulants, as well as essential nutrients found in the leaves. Approximately 12 g of dry mulberry leaves must be ingested for the production of 1 g of dry cocoon shell (efficiency,

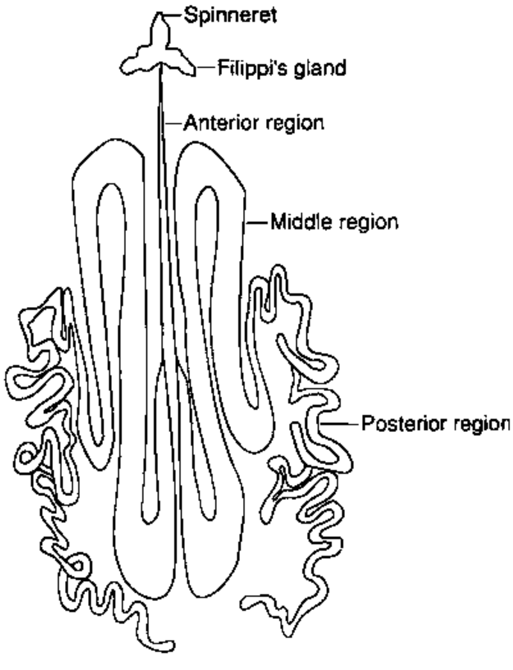


FIGURE 2 Silk glands of *Bombyx mori* larva.

TABLE I

Amino Acid Compositions of the Silk Fibroins from *B.mori*, *P.c.ricini*, *A.pernyi* and *A.yamamai*, and of the Silk Sericin from *B.mori* (mol%)

	B.mori		*P.c.ricini*	*A.pernyi*	*A.yamamai*
Amino acids	fibroin	sericin	fibroin	fibroin	fibroin
Gly	42.9	13.5	33.2	26.7	26.1
Ala	30.0	5.8	48.4	48.1	48.1
Ser	12.2	34.0	5.5	9.1	9.0
Tyr	4.8	3.6	4.5	4.1	3.9
Asp	1.9	14.6	2.7	4.2	4.5
Arg	0.5	3.1	1.7	2.9	3.5
His	0.2	1.4	1.0	0.8	0.8
Glu	1.4	6.2	0.7	0.8	0.7
Lys	0.4	3.5	0.2	0.2	0.1
Val	2.5	2.9	0.4	0.7	0.7
Leu	0.6	0.7	0.3	0.3	0.3
Ile	0.6	0.7	0.4	0.4	0.4
Phe	0.7	0.4	0.2	0.3	0.2
Pro	0.5	0.6	0.4	0.3	0.4
Thr	0.9	8.8	0.5	0.5	0.6
Met	0.1	0.1	Trace	Trace	Trace
Cys	Trace	0.1	Trace	Trace	Trace
Trp	—	—	0.3	0.6	0.7

TABLE II

Composition of Artificial Diets Containing Mulberry Leaf Powder

Substance	Diets for first–fourth instars (g)	Diets for fifth instar (g)
Mulberry leaf powder	25.0	25.0
Soybean oil	1.5	3.0
Defatted soybean meal	36.0	45.0
Cholesterol	0.2	0.2
Citric Acid	4.0	4.0
Ascorbic acid	2.0	2.0
Sorbic acid	0.2	0.2
Agar	7.5	5.0
Salt mixture	3.0	3.0
Glucose	8.0	10.0
Potato starch	7.5	15.0
Cellulose powder	20.8	—
Vitamin B mixture	Added	Added
Antiseptic	Added	Added
(Total)	(115.7)	(112.4)
Water	300 ml	220 ml

8.26%). The weight of the silk glands of the fifth instar larvae increases approximately 100-fold during only 8 days prior to the spinning period. This abrupt increase is attributed to the active synthesis and accumulation of fibroin in the silk glands. This protein is specifically rich in glycine, alanine, and serine , which account for 85% of total amino acids (Table I). These three amino acids must be supplied not only by free amino acids contained in the mulberry leaves, but also by interconversion of other ingested amino acids. Approximately 70% of these amino acids are synthesized *de novo* in late fifth instar larvae.

Efforts have been made to manufacture artificial diets for silkworms for industrial purposes, and fairly satisfactory compositions have been developed. Two examples of artificial diets containing mulberry leaf powder are shown in Table II and are used for practical rearing. Recent development of polyphagous silkworm strains in Japan can be reared to maturity on diet.

The carbon skeleton of *B. mori* silk fibroin is formed mainly from sucrose in mulberry leaves. This disaccharide is decomposed to two hexoses and then metabolized to 3-triphosphoglycerate and pyruvate through the glycolytic pathway and to 2-oxoglutarate in the tricarboxylic acid, TCA, cycle (Fig. 3). Then serine, glycine and alanine are synthesized from these glycolytic intermediates. The nitrogen source for the synthesis of these amino acids may be derived from ammonium split from the degradation of other ingested amino acids and proteins. Ammonium is utilized for the formation of glutamate from 2-oxoglutarate by glutamate dehydrogenase.

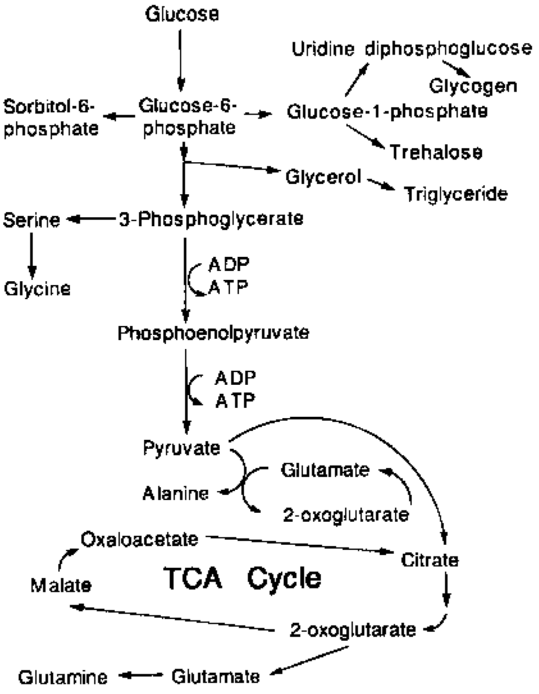


FIGURE 3 Metabolic pathways of glucose in *Bombyx mori* silkworm related to the formation of silk fibroin through glycolysis and carbohydrate reserves. ADP (adenosine diphosphate), ATP (adenosine triphosphate).

III. Silk Structure

A. Primary Structure

The silk fibroin from *B. mori* comprises high-molecular-weight polypeptides containing a predominance of the amino acids glycine, alanine, and serine (Table I). Acid side-chain groups predominate by 2.3-fold over basic side-chain groups. Sericin, which comprises 30% of the cocoon weight, has an amino acid composition that is significantly different from that of fibroin, with a high percentage of serine, aspartic acid, glycine, and threonine residues, which total over 65%. Acid side-chain groups also predominate by 2.6-fold over basic side-chain groups. The hydrophilic nature of sericin permits its separation and removal from the fibroin during the processing of silkworm cocoons in boiling water. Traces of lipid, pigment, and carbohydrate have been reported in *B. mori* cocoons.

B. mori silk fibroin consists of two primary peptides, one approximately 325,000 Da (heavy chain) and the other 25,000 Da (light chain). Silkworm silk can be described as a block copolymer containing crystalline domains (regions of the polypeptide containing the short side-chain amino acids), interrupted with amorphous domains consisting of the bulkier side-chain amino acids. Approximately 70% of the fibroin (sum of the heavy chain and light chain) is the amino acid sequence, Ser–Gly–Ala–Gly–Ala–Gly. A more extended sequence has been reported for the crystalline fraction precipitated after chymotrypsin hydrolysis, as Gly–Ala–Gly–Ala–Gly–Ser–Gly–Ala–Ala–Gly–[Ser–Gly–(Ala–Gly)$_n$]$_8$-Tyr, where n is usually 2. This sequence accounts for 55% of fibroin. Other characteristics of the primary structure of fibroin are the absence of the sequence Gly–Gly and the presence of the sequences, Gly–Tyr–Gly and Gly–Val–Gly (tyrosine (Tyr) and valine (Val)). Thus, *B. mori* fibroin is regarded as an alternate copolymer of Gly. There have been no detailed reports on the amino acid sequence of sericin.

B. Secondary Structure

Different types of silk can exhibit a variety of characteristic protein secondary structures, including β-sheets, cross-β sheets, α helices, and random coils. *B. mori* cocoon silk is characterized by the β-sheet secondary structure wherein the protein polymer chains run antiparallel to each other interact and interact through hydrogen bonds (Fig.4). The polymer chains run parallel to the fiber axis. Overlying sheets in the secondary structure interact by hydrophobic attractions to further stabilize the structure. The tight packing density of the overlying sheets is due to the high percentage of short side-chain amino acids consisting of approximately 85% (glycine + alanine + serine in a 3:2:1 ratio).

Two key crystalline structures have been identified for silkworm silk, silk I and silk II. The silk I conformation represents the water-soluble form present when silk is first synthesized in the posterior region of the silk gland. The silk II form represents the water-insoluble conformation present in the spun silk fiber. The unit cell dimensions for both crystalline structures of native silk are shown in Table III ; the silk I dimensions are based on predictions from conformational energy calculations with glycine–alanine repeats, while the silk II data are based on X-ray diffraction studies. The change in unit cell dimensions during the transition from silk I to silk II during fiber spinning is most dramatic in the intersheet plane, with a decrease of 18.3% between three overlying sheets, which excludes water and reduces solubility. The silk II form is more energetically stable, and though the energy barrier from silk I to silk II is relatively low, the transition is generally considered irreversible. The transition occurs in the silk-producing gland of the silkworm from shear during the spinning process. Artificially, the same transition can be induced by mechanical shear or drawing, heat, use of polar solvents such as methanol and acetone, and under the influence of electric fields.

IV. Silk Properties

A. General Characteristics

Silkworm silk is insoluble in water, dilute acids and alkali, and most organic solvents. In addition, silks are resistant to most proteolytic enzymes. Silk fibers are hygroscopic, with a moisture regain of 10 to 15%. Other physical properties include a characteristic translucence with high lustre or sheen, abrasion resistance, ability to bind dyes, resistance to environmental degradation because of their resistance to proteolytic enzymes, and susceptibility of the undyed fiber to sunlight. The specific gravity for silkworm silk is 1.25.

B. Mechanical Properties

Silk fibers combine strength and toughness. For example, silkworm silk exhibits up to 35% elongation

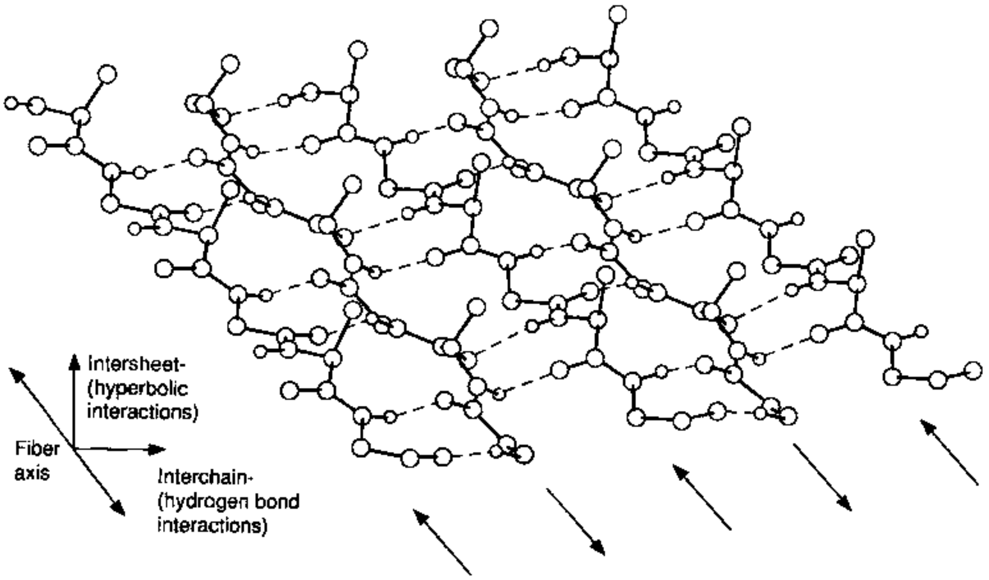


FIGURE 4 Generalized picture of the anti-parallel β-sheet structure (single sheet shown) for the crystalline regions of silk. Note: polymer chains run according to the arrows, thicker lines indicate covalent linkages, while the dotted lines represent hydrogen bonding between neighboring chains (carbonyl groups on one chain and amine groups on the neighboring chain). The methyl side chains from the alanine amino acids all project upward on the same side of the sheet structure shown. Overlying sheets (not shown) would interact through hydrophobic interactions.

with tensile strengths approaching those of high strength synthetic fibers. The tensile strength for silkworm silks is approximately $6 \times 10^8 N/m^2$, the modulus is approximately $5 \times 10^9 N/m^2$, and the energy to break is approximately $7 \times 10^4 J/kg$. This is particularly impressive when considering that natural silk fibers undergo minimal draw to enhance molecular orientation, which improves mechanical properties. Unlike most fibers, increased rates of loading of silk fibers result in increased strength and modulus as well as elongation; this increases the amount of work to rupture. The mechanical properties of silkworm silks have been shown to correlate in part with the ratio of long side-chain amino acids to short side-chain amino acids in the fibroin, high ratios correlating with higher elongation and lower tenacity.

TABLE III
Unit Cell Dimensions for Silk I and Silk II

Dimension	Silk II	Silk I
a axis (intersheet distance)[a]	0.920 nm	1.126 nm
b axis (interchain distance)	0.944 nm	0.894 nm
c axis (fiber axis)	0.697 nm	0.646 nm

Note. The silk II values are based on X-ray diffraction data and the silk I values are based on predictions from conformational energy calculations.

[a] intersheet distance between three overlying sheets (p.530 and 0.390 nm silk II, 0.565 nm for silk I)

V. Silk Processing

A. Solution

It is very important to be able to obtain an aqueous solution of silk fibroin in order to use it in biomaterials as described below. It is possible to get a solution of fibroin directly from the glands, where the concentration is 12–15% in the posterior silk gland and approximately 20–30% in the middle silk gland. An aqueous solution of silk fibroin can also be obtained from raw silks or cocoons indirectly. A degumming process, desericinization with boiling soap solution or boiling dilute Na_2CO_3 solution, is used to obtain only silk fibroin fiber. Such a fibroin is soluble in certain concentrated aqueous salts; dialysis removes these salts and leaves the fibroin in aqueous solution. Salts that have been extensively used in this way are LiBr, LiSCN, and $CaCl_2$.

It has been established that in dilute aqueous solution, *B. mori* silk fibroin exists in a random coil structure. However, with slow concentration at room temperature, the side-by-side chain aggregation of the fibroin molecules occurs and as a result, fluctuations around the backbone bonds decrease, generating a silk I conformation . The content of silk I of the silk fibroin stored in the middle silk gland is about 40%.

B. Films

Films of *B. mori* fibroin are prepared by air-drying an aqueous solution cast on a film of poly(vinylidene chloride) or acrylic resin plates. The conformation of these films usually consists of silk I and random coil. The fresh films are usually water-soluble. Hydration by placing the films in a closed chamber of about 100% relative humidity for 24 hr stabilizes the silk I form and the membrane becomes water-insoluble. By immersing water-soluble films into polar hydrophilic solvents such as methanol and acetone, the conformational transition to the silk II form occurs at the surface of the films which become water-insoluble. However, fibroin molecules in inner parts of the films are still in random coils and the backbone chains are mobile in water, that is, the films become heterogeneous in structure. The water-insoluble films are also obtained by the stretching treatment of the water-soluble films. In addition, preparation of a porous fibroin film is possible by adding polyethylene glycol to an aqueous solution of fibroin. This causes a conformational transition to silk II and the dried film becomes water-insoluble. After immersing the films into water, porous fibroin films are obtained by the removal of polyethylene glycol.

C. Fibers

In sericulture silkworm cocoons are harvested and immersed in a hot soapy water bath to solubilize and remove the sericin in a degumming operation. The remaining silk fiber in the cocoon is then reeled by either hand or machine and subsequently dyed or chemically treated (e.g., to reduce wrinkling, improve washability) depending on the intended application for the fibers. The reeled fibers are usually woven into textiles.

Rheology studies with soluble silk indicate that the degree of crystallinity of the silk fiber correlates with shear rate and draw rate, and that a critical extrusion rate of slightly under 1-cm/sec is necessary to induce a conformational shift to the silk II secondary structure and for the appearance of birefringence. In the natural spinning process, the silk polypeptides in the posterior region of the gland are water-soluble and optically featureless and exhibit a range of secondary structures including random coil. This region of the gland is less than a millimeter in diameter and the shear rate is low. In the middle region or storage area of the gland, the diameter is 1.2 to 2.5 mm and the shear rate is also very low. In the anterior region of the gland the diameter is very narrow, 0.05 to 0.3 mm, the shear rate is very high, there is active water transport out of the gland, there is a decrease in pH, and there is ion exchange particularly with potassium, sodium and phosphates. It is assumed that at this stage the silk begins to take on the predominant β-sheet secondary structure. The diameter of the fiber can vary depending on the rate of spinning and the diameter of the silk fiber changes in the different layers of the cocoon. The total length of the fiber is presumably determined by the rate and duration of protein synthesis.

The viscosity of the protein solution in the anterior region of the gland decreases due to the formation of a lyotropic liquid crystalline phase. This phase apparently helps to avoid premature clogging of the spinning apparatus by aiding the flow of the material and reducing the processing energy requirements by the organism. An added benefit for this process is the high degree of molecular orientation and alignment achieved with the combination of the liquid crystalline phase and the spinning process itself. This orientation is achieved with minimal draw and imparts to the fibers their unusual mechanical properties. A nematic liquid crystalline phase has been demonstrated by isolating the protein solution from the silk gland and allowing it to gradually dry on a shear stage of an optical microscope. This phase is characterized by axial alignment and interaction of polymer chains in various stages of registry with each other while remaining soluble in the aqueous medium. The role of sericin during fiber formation, aside from serving as the matrix to hold the two fibroin fibers together, may be to aid the passage of the silk polypeptides through the spinneret, to serve as a reservoir of divalent cations, and to act as a receptor for water coming from the fibroin.

VI. Gene Structure and Function of Silk

A. Gene Structure

Silks are encoded by highly repetitive structural genes that are under tight regulatory control in the cell. The repetitive domains influence the higher-order conformation and result in fibers with unusual functional properties. The structure of the fibroin gene has been partially described. The gene encoding the fibroin heavy chain is reported to be on the order of 16 kb and to contain, in order, a 5′ adenine/thymine-rich flanking region, a 970-bp intron , a short nonrepetitive coding region (414 bp), a core repetitive region of approximately 15 kb containing 10 crystalline domains of 1 to 2 kb each interspersed with amorphous domains containing about 220 bp, and an untranslated flanking region at the 3′ end. Restriction maps of the fibroin gene have been generated. Due to the guanine/cytosine-rich content of the crystalline domains of the gene many restriction enzymes do not cut or cut rarely in the core repetitive region of the gene which makes internal mapping difficult. Only a small fraction of the total gene has been sequenced. The gene encoding the fibroin light chain has also been sequenced. The synthesis of the heavy and light fibroin chains is jointly regulated such that equimolar amounts of the two polypeptides are formed; however, the two genes are located on different chromosomes. Joint synthesis and secretion of the fibroin heavy and light chains is dependent on covalent crosslinking between the two chains which occurs post-translationally through a disulfide link. Sericins are encoded by at least two genes, with different gene splicing events giving rise to different sericin mRNAs ranging in size from 2.8 to 10.5 kb.

B. Gene Regulation

The high level of protein production within a specific stage in the life cycle of the silkworm has prompted strong interest in understanding the regulation of the system, as well as for the potential use of *B. mori* as a host system to express genetically engineered proteins once suitable gene transfer systems are developed. Genetically engineered viruses have been used to infect fifth instar larvae of *B. mori* to produce nonsilk proteins (pharmaceuticals) such as interferon and interleukin. Expression of the fibroin gene is localized to the epithelial cells lining the posterior region of the silk gland, similarly, expression of sericin is limited to the middle region of the gland. Tight transcriptional controls exist in the cell for both types of genes. For example, activation of fibroin gene transcription starts from the anterior part of the posterior silk gland at the beginning of the fifth instar and spreads toward the posterior end of the gland. Although only a single copy of the fibroin gene exists per haploid genome, the mRNA formed is very stable with a half life of several days. This enables the gradual accumulation of large amounts of the message which accounts for the high rates of fibroin synthesis at the end of the fifth instar. Strong translational controls are also required to permit the high level of production of protein in this system. Silk gland-specific tRNAs and tRNA synthetases are required to support the high levels of glycine, serine, and alanine amino acids for both fibroin and sericin synthesis. The expression *in vitro* of at least tRNAala is under the control of tissue-specific transcription factors which bind both upstream and internal to the gene. There is also a requirement for a class of transcriptional regulatory RNA (TFIIIR) described for the first time in this system. In a cell-free system supplemented with insect tRNAs (particularly those for glycine, alanine, and serine), as well as in silk gland maintained in culture, discontinuous translation patterns were noted, with increasing sizes of peptide chains up to full length. The discontinuous nature of the translation (which results in a series or ladder of polypeptide chains of increasing size) corresponds to the different times required for ribosomal recognition-binding at each codon and may be due to suboptimal concentrations of specific tRNAs due to the preponderance of glycine, alanine, and serine (approximately 85%) in the peptide. This relates to the repetitive nature of the gene and the encoded protein.

The compartmentalization of the silk gland, with sericins produced in the middle region and fibroins in the posterior, provides a significant level of control over silk expression and processing. In both cases, primary transcription is controlled by the presence of specific DNA binding proteins (transcription factors) which interact with the flanking or control regions associated with each class of genes to form active transcription complexes. The specialization of the posterior silk gland for high levels of fibroin protein synthesis appears to be primarily controlled by the expression and high stability of its mRNA, which is synthesized continuously in the posterior silk gland except at molts, and thus accumulates to very high levels by the middle of the fifth instar.

VII. New Applications of Silk

A. Textile (hybrid silk)

A hybrid silk composed of fine silk at the surface of a synthetic fiber core was recently commercialized. It is produced by extruding silk and nylon together through an air jet nozzle with a nylon filament placed at the center and five raw silk filaments (2 denier each) twined around the nylon core. The hybrid fiber retains excellent handling and a good silk luster as well as having the fiber strength of nylon. When stockings made from this hybrid silk are degummed to remove surface sericin, they show a metallic-silver luster. The fibroin threads also increase in thickness because of thermal shrinkage of the nylon core. This product is, therefore, a genuine hybrid of silk and nylon, and yields quite different characteristics from those of a conventional blended yarn of the two fibers.

B. Biocosmetics

Fatty deposits on the skin surface can be removed by washing with soap. Protein deposits from skin, however, cannot readily be removed unless they are first hydrolyzed with a proteinase. Some conventional cosmetics contain proteinase, but its hydrolysis activity deteriorates rapidly with time, particularly when left with surfactant in the wet state. Many attempts have been made to stabilize the proteinase activity in cosmetics. Proteinase immobilized in fibroin powder is stable to heat and its hydrolysis activity lasts for a considerable period of time, since fibroin protects the enzyme against heat and moisture. Thus, granules of mixed proteinase-encapsulated fibroin powder and detergent have been successfully developed for this purpose.

C. Biosensors

As a support for enzyme immobilization, silk fibroin has certain, several inherent advantages. First, in the preparation of an enzyme-immobilized film with fibroin, simultaneous insolubilization of the water-soluble film and immobilization of the enzyme in the film is possible without any chemical reagents for crosslinking. This is based on the fact that conformational transition of the silk fibroin chain is induced easily by various treatments, such as drawing, compression, and immersion in alcohol, or hydration under high humidity. The sensor was prepared with a glucose oxidase (GOD)-immobilized silk fibroin film attached on an oxygen electrode surface and assembled in the apparatus shown in Fig. 5. Moreover, a fourfold increase in sensitivity was observed when the glucose sensor was made with the GOD immobilized on nonwoven silk fabrics compared with a GOD-immobilized silk fibroin film. The membrane potential of the GOD-immobilized silk fibroin film is induced by an enzymatic reaction after the addition of the substrate glucose. An application for the process has shown by the preparation of a new type of glucose sensor, which functions without an oxygen electrode. Biophotosensors have also been made, using fibroin films with immobilized peroxidase.

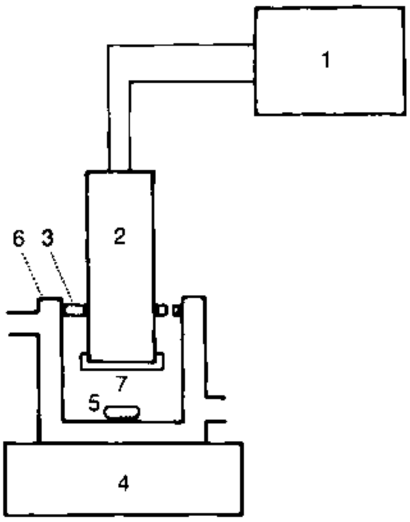


FIGURE 5 Apparatus for determination of immobilized GOD activity: (1) recorder; (2) oxygen electrode with Teflon film; (3) silicone ring; (4) magnetic stirrer; (5) stirring bar; (6) reaction cuvette; (7) GOD-immobilized film. (This film was attached when apparatus was used as a glucose sensor.)

VIII. Wild Silkworm Silks

A. Silk Structure

Many kinds of wild silkworms produce silk. The classification of common silkworms is shown Fig. 6. Those which are reared for cocoon production are *Antheraea yamamai*, *A. pernyi*, *A. mylitta*, and *Philosamia cynthia ricini*. The characteristics of these cocoons, including those of *B. mori*, are summarized in Table IV. The cocoons of the wild silkworms also mainly consist of silk fibroin and sericin, but the content of sericin is relatively low as is expected from the fact that the size of middle region of the silk gland is more slender than that of posterior region of the gland. In addition, the content of lipid, pigment, and carbohydrate is relatively high compared with that of *B.mori* cocoons.

Table I shows the amino acid compositions of silk fibroins of *P. cynthia ricini*, *A. pernyi* and *A. yamamai*. The major amino acid residues of these wild silkworm fibroins are alanine and glycine; as with *B.mori*, the sum of these two amino acid residues comprises

TABLE IV
Characteristics of cocoons

	Cocoon color	Thickness and stiffness of cocoon shell	Size of cocoon (width × length, cm)
Bombyx mori	White	Thick,hard	2.5 × 3.5
Antheraea yamamai	Greenish-yellow	Thin,hard	2.3 × 4.5
Antheraea pernyi	Brown	Thin,hard	2.3 × 4.5
Antheraea mylitta	Brown	Thick,hard	(2.3–3.5) × (3.5–6.5)
Philosamia cynthia ricini	Pale brown	Flossy	1.5 × 4.5

74–82% of the silk fibroin (Table I). However, the relative content of alanine is larger than that of glycine, in contrast to the case of *B.mori* fibroin, where the reverse is the case. As a result, the most striking conformational characteristic of these silk fibroins in the silk gland or in aqueous solution is the presence of α-helical domains consisting of only alanine residues. The average number of alanine residues in such an α-helical domains has been reported to be 22 for *P.c.ricini*. With increasing temperature, a conformational transition from α helix to random coil occurs and the helix content of whole silk fibroin decreases from 26% (0°C) to 15% (25°C). Such a conformational transition from an α helix to random coil is also observed directly in living silkworm. After spinning, the conformation of the silk fibroin changes from α helix and random coil to mainly anti-parallel β-sheet structure (silk II). The amino acid compositions of the sericins of these wild silkworms are similar to those of *B.mori*.

B. Silk Properties and Processing

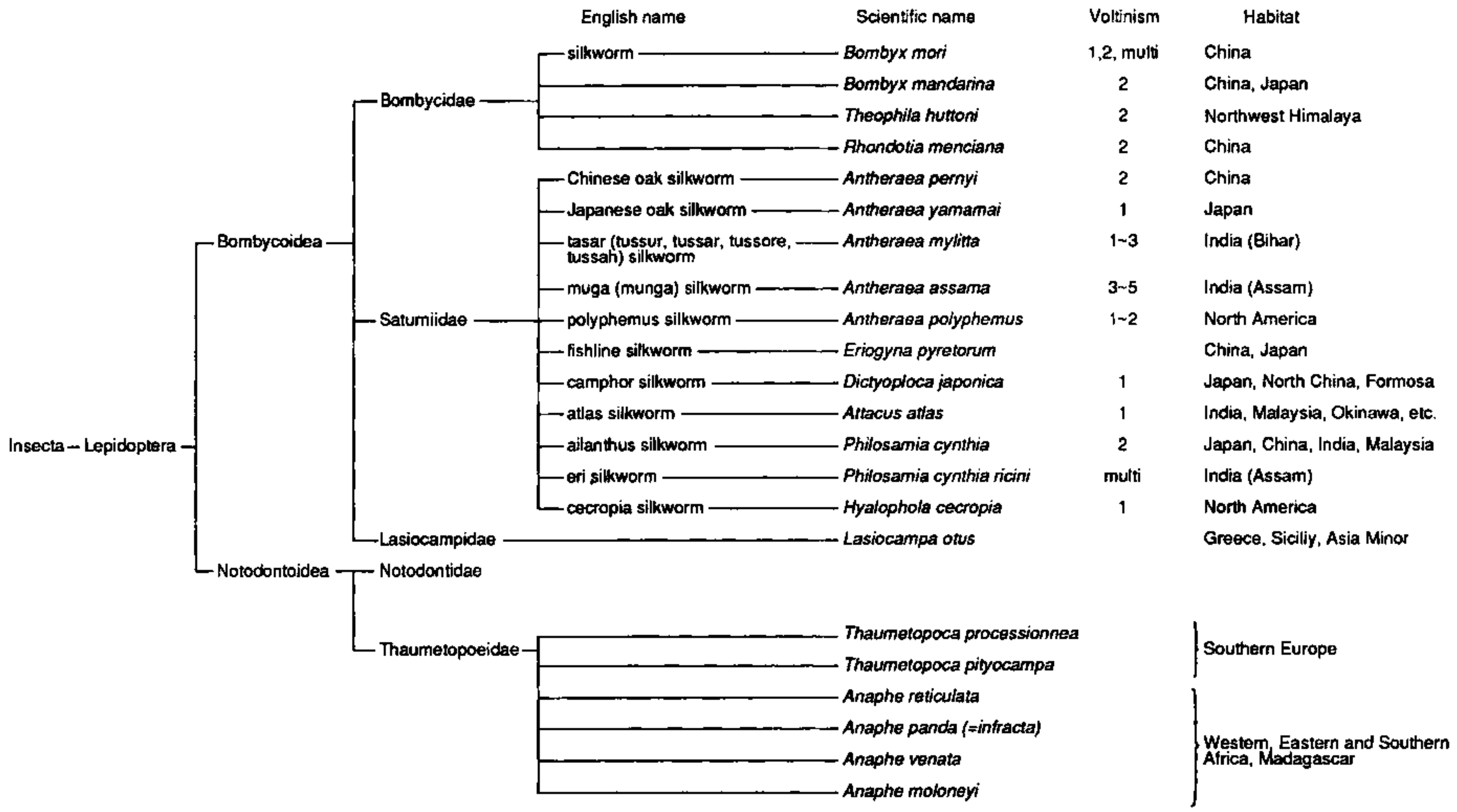
The characteristics of wild silkworm fibroin fibers are considerably different from those of *B. mori* silk fibroin fibers, producing woven goods with different physical and mechanical properties. For example, the values of the modulus of *A. pernyi* and *A. yamamai* silk fibers are smaller than that of *B. mori* silk fiber. In addition, the load increases more slowly with increasing extension in the load-extension plots of *A. pernyi* and *A. yamamai* fibers compared to *B. mori* fiber. Other differences include a lower hygroscopic property and different dying characteristics compared with *B. mori* fiber.

An aqueous solution of *P.c.ricini* silk fibroin with α-helical domains can be obtained from the posterior region of the silk gland and a cast film of fibroin can be prepared by a preparation similar to that described for *B. mori* fibroin . A water-insoluble film is obtained by drawing or immersing it in methanol causing a conformational transition from α helix or random coil to β forms to occur. This film can be also used for the immobilization of GOD and applied to a glucose sensor. It is of special interest that the thermal stability of *P.c.ricini* films is higher than that of *B. mori* film.

IX. Spider Silk

A. Silk Structure

Over 35,000 species of spiders have been identified, representing some of the most diverse and abundant organisms in nature. Web building spiders produce silks for the purpose of catching prey; however, unlike the silkworm, the silk production and collection processes from spiders have never been domesticated. Spiders can produce a variety of different silks, some of which are formed throughout their life cycle. Techniques for the controlled silking of spiders have been developed and under such conditions, *Nephila clavipes*, the golden orb weaver, can produce up to 200 g of silk protein fiber in a single silking session. Females are primarily responsible for orb-web construction and webs are often recycled by the spider. Aside from functioning in prey capture, the different spider silks are used in reproduction, adhesion, dispersing of young by the wind, and as vibration receptors for prey detection. Visual displays on webs, such as the zigzag stabilimenta pattern characteristic of certain orb webs, may function to stabilize or strengthen the web, disguise the spider, warn off birds from damaging the web, or absorb water. Some spiders produce only one type of silk, while others may produce up to 10 or more different kinds of silk, each for a different function. The different silks are produced in different sets of specialized glands in the



English name	Scientific name	Voltinism	Habitat
silkworm	*Bombyx mori*	1,2, multi	China
	Bombyx mandarina	2	China, Japan
	Theophila huttoni	2	Northwest Himalaya
	Rhondotia menciana	2	China
Chinese oak silkworm	*Antheraea pernyi*	2	China
Japanese oak silkworm	*Antheraea yamamai*	1	Japan
tasar (tussur, tussar, tussore, tussah) silkworm	*Antheraea mylitta*	1~3	India (Bihar)
muga (munga) silkworm	*Antheraea assama*	3~5	India (Assam)
polyphemus silkworm	*Antheraea polyphemus*	1~2	North America
fishline silkworm	*Eriogyna pyretorum*		China, Japan
camphor silkworm	*Dictyoploca japonica*	1	Japan, North China, Formosa
atlas silkworm	*Attacus atlas*	1	India, Malaysia, Okinawa, etc.
ailanthus silkworm	*Philosamia cynthia*	2	Japan, China, India, Malaysia
eri silkworm	*Philosamia cynthia ricini*	multi	India (Assam)
cecropia silkworm	*Hyalophola cecropia*	1	North America
	Lasiocampa otus		Greece, Siciliy, Asia Minor
	Thaumetopoca processionnea		Southern Europe
	Thaumetopoca pityocampa		
	Anaphe reticulata		Western, Eastern and Southern Africa, Madagascar
	Anaphe panda (=infracta)		
	Anaphe venata		
	Anaphe moloneyi		

FIGURE 6 Classification of common silkworms.

TABLE V
Examples of the Different Types of Spider Silk Protein Polymers and Their Functions

Gland	Type of silk	Function
Major ampullate	Dragline, orb frame, radii	Saftey line, mechanical strength
Minor ampullate	Orb frame, dragline	Support fibers—frame and dragline
Flagelliform	Viscid	Prey capture
Aggregate	Gluelike	Prey capture and retention
Cylindrical	Cocoon	Reproduction
Aciniform	Wrapping	Captured prey
Piriform	Attachment	Coupling to environmental substrates

abdomen of the spider (Table V). Each of these silks has a different amino acid composition and presumably a different amino acid sequence, giving rise to the differing functional properties and roles in the lifecycle of the spider. Generally, spider silk orb web fibers are smaller in diameter than silkworm fibers, usually ranging from 1 to 5 m. Soluble organic chemicals, salts, and water on the surface of web fibers appear to play a role in species identification and in maintaining the mechanical properties of the fibers. Dragline silk is the strongest of the spider silks, and unlike the cocoon silk of the silkworm, does not appear to contain sericin gluelike proteins. In addition, only one polypeptide has been reported to date in the dragline silk, with a molecular weight in excess of 300,000 Da. The amino acid composition of spider dragline silk from *N. clavipes* indicates a lower percentage of short side-chain amino acids (glycine, alanine, serine) than the silkworm cocoon silk, totalling 63 vs 85%, respectively. Spider dragline silk exhibits a lower degree of crystallinity than silkworm silk.

B. Silk Properties and Processing

Spider dragline silk generally exhibits almost an order of magnitude enhancement in mechanical strength when compared with silkworm silk. Therefore, there is a great deal of interest in a variety of high-strengh fiber applications for these proteins. The mechanical properties of spider silks correlate to their function in absorbing the impact of flying insects without breaking. The orb-web dissipates energy over a broad area by balancing stiffness, strength, and extensibility. The majority of the energy of impact is lost as heat through viscoelastic processes in the web. This avoids an elastic recoil which could potentially eject the insect back out of the web. Unrestrained spider silk fibers from the web (major ampullate gland) are reported to supercontract to almost half their original length upon exposure to water. The minor ampullate gland silks do not exhibit this behavior, nor do silkworm silks. A lyotropic liquid crystalline phase has also been demonstrated with a number of different spider silks.

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Silviculture

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Glossary

Advanced regeneration Trees that appear spontaneously or are induced to appear beneath existing stands

Forest stand Aggregation of trees with sufficient uniformity of species composition, age(s), spatial arrangement, or condition as to be distinguishable from adjacent aggregations and large enough to be treated separately for purposes of forest management

Regeneration or **reproduction** Act of renewing aggregations of trees either naturally or artificially or the small trees resulting from the renewal

Regeneration or **reproduction methods** Tree removal treatments made to create conditions favorable for establishment of regeneration

Microenvironment Small space throughout which the physical, chemical, and biotic environmental factors are uniform in their ecological effect

Rotation Period of years elapsing between the initiation of a new crop of trees and its final harvest

Silvicultural system Program of silvicultural treatment of a stand that extends throughout the life of the stand

Tending or **intermediate cutting** Treatments carried out during the life of a stand in order to improve it, regulate its growth, or obtain early financial returns but not to regenerate it

Silviculture is the theory and practice of controlling the establishment, species composition, structure, and growth of forests. It is to forestry as agronomy is to agriculture. Almost all the natural and social sciences are applied to the design of silvicultural solutions to the wide variety of problems, objectives, and circumstances encountered at each stand and site.

I. Purposes of Silviculture

Silviculture can be applied to cause forest stands to yield such benefits as wood, water, wildlife, forage, recreation, and aesthetics in settings varying from urban to wilderness. Ordinarily two or more uses are pursued simultaneously in the same stands. The combinations depend on the priorities and limitations imposed by the objectives of owners and of public land-use policies. These vary widely but it is very difficult to formulate silvicultural systems for particular stands unless the priorities attached to each kind of use are clearly defined.

Some uses are well-nigh universal. In most forests precipitation exceeds evapotranspiration during some season so surpluses of water flow to streams or groundwater. Therefore, water supply becomes a matter of public policy regardless of whether the landowner uses the water. Likewise, all forests have wildlife which is often treated as a kind of public property; it may be a benefit used by people or a source of damage to the vegetation; in any event, silviculture can play a key role in the construction and management of wildlife habitats.

II. Silviculture as Simulation of Natural Processes

Silviculture is a low-intensity form of plant culture in which one intervenes in natural processes only at infrequent crucial stages and more often guides rather

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than alters their progress. It is applied forest ecology (see below) in which the natural processes of stand development and the lethal disturbances that initiate new stands are imitated. [*See* FOREST ECOLOGY.]

In most silvicultural treatments vacancies are created in the total growing space to make room for new plants or to give existing plants more space in which to expand. The vacancies are normally created by killing trees, often but not always in the act of harvesting them. The *growing space* is the combination of the stratum of soil that can be occupied by plant roots and the stratum above ground into which tree crowns can reach. Vegetation tends to refill such vacancies. Because of their ability to grow tall, forest trees can fill growing space more completely than other plants.

Fire, one of the the most common kinds of natural lethal disturbance, is more likely to kill small trees than large ones. The small new trees that follow fire germinate or resprout after fire. Other kinds of lethal disturbance, such as wind and pests, usually kill from the top of the old stand downward rather than from the bottom up. The species that are adapted to take advantage of such disturbances are often ones that start as preestablished *advanced regeneration* before the disturbances that release them to grow. Usually they are tolerant of partial shade and root competition from the older trees.

However, if fire burns the large amounts of dry fuel left by windstorms, pest outbreaks, or similar events all preexisting vegetation is likely to be completely killed although true soil generally remains. Some so-called pioneer species such as jack and lodgepole pine can recolonize from seed after such fires but artificial planting is the common silvicultural simulation of this lethal combination. Fire can also cause some species to resprout from basal sprouts or roots. Some pioneer species are adapted to germinate on bare mineral soil exposed by natural agencies other than fire, such as animals or the uprooting of trees by wind.

Natural events such as landslides or volcanic eruptions that expose raw parent material rather than true soil constitute the most severe natural disturbances. These are seldom deliberately simulated in silvicultural practice, although the reforestation of deeply eroded areas and mine spoil banks is an unplanned simulation.

Nature is not imitated slavishly or precisely. It is instead a case of knowing which natural processes to simulate and which to prevent, redirect, or modify.

III. Kinds of Forest Stands

Stands of trees vary as to the number of age classes and species that comprise their structure (Fig. 1). The simplest kind is *even-aged* (with one age class) and *pure* (composed of a single species). *Uneven-aged stands* have three or more age classes. A *balanced uneven-aged stand* would have all age classes evenly spaced as to age, from very young to mature, with each class covering an equal area; these are really theoretical constructs that are almost impossible to create. Stands with two age classes are maintained mainly where one category of trees is allowed to live much longer than another. The different kinds of age-class structure are most easily recognized in pure stands.

Pure stands are often found in nature because the combination of dry soils and fire commonly favors one species over all others. They are also often created artificially either because of simplicity of management or because some single species is deemed ideal.

The development of mixed stands is complicated and less predictable. They are most common where favorable soil moisture conditions make it possible for many species, or at least more than one, to grow. Since different species seldom grow at exactly the same rate in height the species tend to sort themselves out into different strata. Species that can endure shade are in fact often adapted to exist in the lower levels of such *stratified mixtures* (Fig. 2); these combinations of species generally utilize light more completely than is possible for one alone. Some species may share the same stratum but not necessarily throughout the life of a stand. The different strata are designated sequentially by letters with A denoting the uppermost even if it consists only of isolated *emergents* that project higher than their neighbors.

The structure of mixed stands can be further complicated by inclusion of different age classes. As is true of age classes in general these can usually be identified by differences in the height of the top of the crown canopy. Total height is the best indicator of ages of free-growing trees, except that it is modified by the ability of the soil to supply water and nutrients; the better the soil the faster the trees grow in height. The effect of age on tree diameter is so variable that it is a poor indicator of age. This is why the distributions of diameter in relation to age shown in Fig. 1 for even-aged stands are normal distribution curves

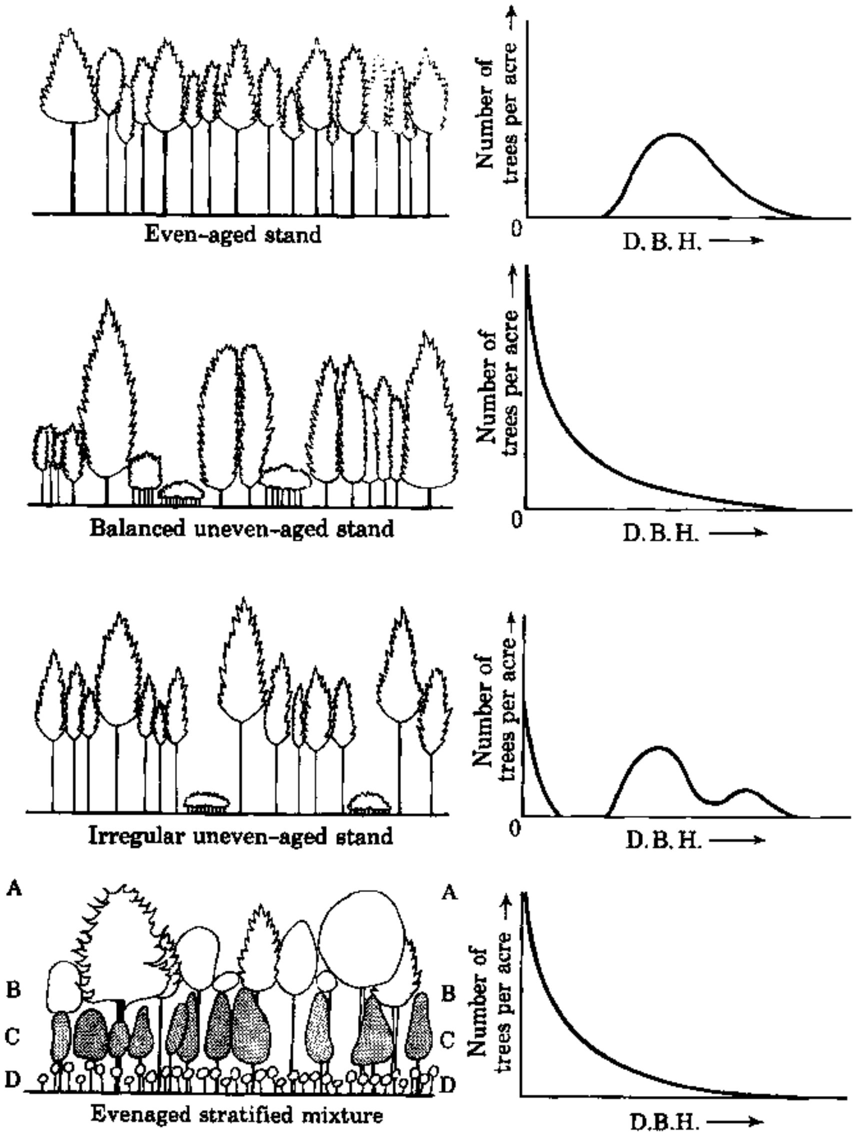

FIGURE 1 Four kinds of forest stand structure with their corresponding curves of distribution of tree diameters. The trees of the first three stands are all of the same species but the fourth consists of several species all of the same age. The four horizontal strata of the stratified mixture are lettered A, B, C, and D. [D.B.H., diameter at breast height (4.5 ft)] [Reprinted with permission from Smith, D. M. (1986). "The Practice of Silviculture," Fig. 1-3, p. 17. Copyright © 1986 by John Wiley & Sons, Inc., New York.]

(truncated at the low end because of competition-induced mortality of small trees).

IV. Regeneration

A. Ecology of Germination and Establishment

Forests are renewed by creation of vacancies in growing space suitable for the initiation and survival of new plants. The natural vegetation of any locality generally includes species adapted to colonize any habitable vacancy that has been created in nature. Knowledge of the adaptability of desired species is the key to knowing what kinds of vacancies to create. These vacancies are best thought of as microenvironments because the most crucial stages of life of new seedlings are passed in the space of a few centimeters.

These microenvironments are regulated mainly by adjusting the light and moisture conditions of each

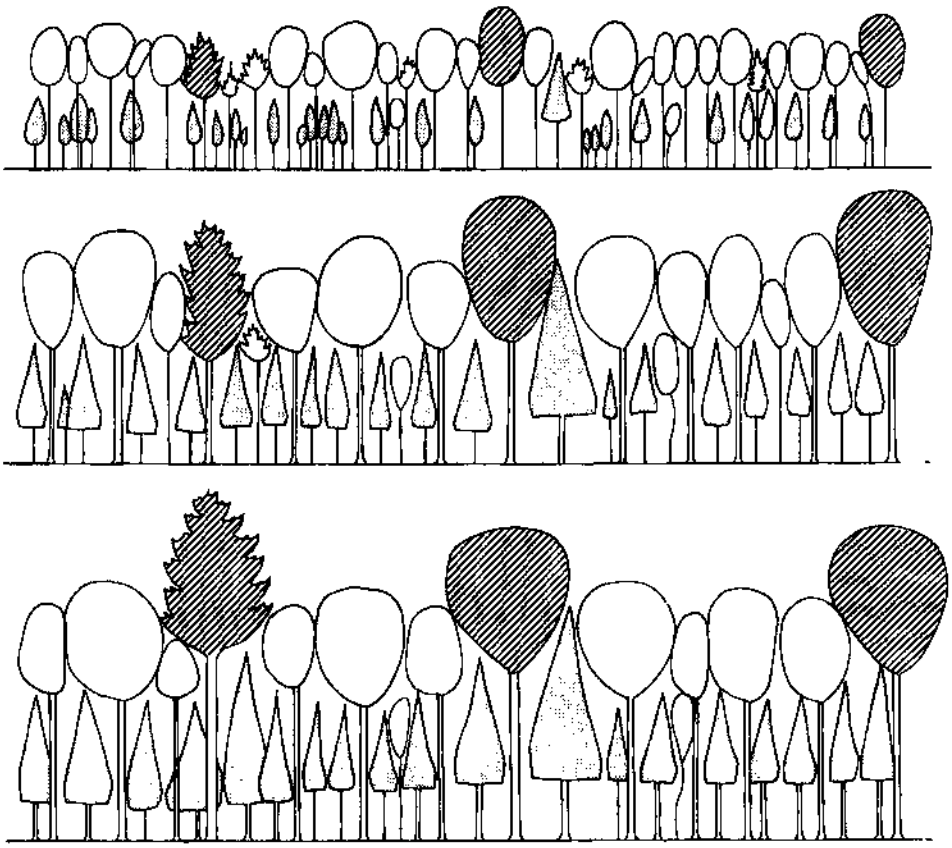

FIGURE 2 Stages in the natural development of a stratified mixture in an even-aged stand of eastern hemlock, hardwoods, and easter white pine. The upper sketch shows the stand at 40 years with the hemlock (*gray crowns*) in the lowest stratum beneath an undifferentiate upper stratum. By the 70th year (*middle sketch*) the emergents of the A stratum *(hatched crowns)* have ascended above the rest of the mai canopy (B stratum), except that the white pine *(jagged crown)* has only started to emerge. The lower sketch shows the stand at age 12 with the ultimate degree of stratification with the hemlock in the lowest C stratum. [Reprinted with permission from Smith, D. M (1986). "The Practice of Silviculture," Fig. 17-3, p. 495. Copyright © 1986 by John Wiley & Sons, Inc., New York.]

spot by shading, reduction of preexisting vegetation, and physical treatment of the soil surface. Some pioneer species germinate in full light on bare soil like many agricultural annuals. Most tree species, however, require some protection from the extremes of temperature that occur on soil surfaces exposed to direct sun and open sky. Water losses from direct evaporation can make exposed surfaces too dry for most seeds to germinate.

Sometimes ideal conditions exist in side-shade where there is no direct solar radiation except for sunflecks but plenty of diffuse sky light. Some species are so tolerant of shade that they can start in very small vacancies beneath nearly closed stands of overhead trees. In other words, the species composition can be partly governed by determining whether establishment of new trees is sought in (a) the open, (b) along stand edges, or (c) beneath canopy shade. Figure 3 shows how cutting patterns can be altere to create these different conditions. New trees tha are adapted to start underneath other trees usuall grow slowly in height at first but remain capab of initiating rapid growth when the trees above ar removed. Many species require less and less shad as they go from the germination stage, to that o establishment, and then to a subsequent one of vigo-ous height growth.

Small-seeded species usually germinate best at o very close to the surface of bare mineral soil or son other medium that provides close contact with steady supply of water. Large seeds, on the othe hand, usually need to be buried beneath litter or soi in nature, this is often done by rodents. Species wit large seeds have abundant food reserves so their see-lings are more able to survive at low light intensi than those with very small seeds.

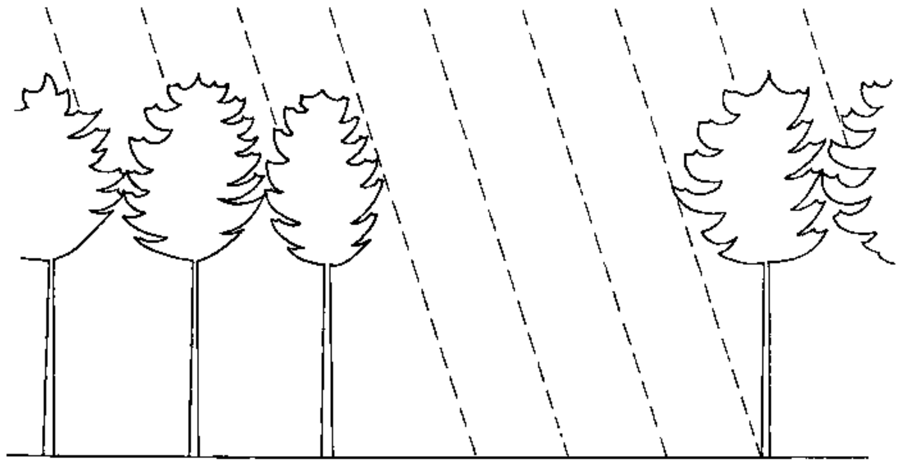

FIGURE 3 Zonation of solar radiation across an opening cut in a stand showing the zones of incidence of the slanting rays of direct sunlight, the diffuse light that comes most abundantly from the sky straight above, and the transmitted light (including sun flecks) that come through the leaves of the trees. [Reprinted with permission from Smith, D. M. (1986). "The Practice of Silviculture," Fig. 7-4, p. 206. Copyright © 1986 by John Wiley & Sons, Inc., New York.]

B. Sources of Regeneration

The simplest source of forest tree regeneration is the kind of seed which falls from the parent tree, germinates, and produces a seedling that promptly initiates rapid height growth. However, regeneration can also arise from vegetative sprouts produced by the parents and there are also ways in which seeds or slow-growing seedlings are stored on the site.

The seeds of some species, usually fire-followers such as lodgepole and jack pines or eucalypts, can be stored for many years in cones or fruits that open during fires. Some hard-coated seeds remain stored in the soil until conditions of heat, moisture, or light favor germination.

Many species are adapted to becoming established as advanced regeneration which starts beneath old stands, grows slowly and persists until it is released from overhead competition. This kind of regeneration can sometimes be induced by reducing the amount of shade gradually in series of partial cuttings called shelterwood cuttings.

Some species are adapted to grow slowly in height during the early years until they have developed root systems extensive enough to provide water sufficient for more rapid growth. Longleaf and some subtropical pines may, for example, not grow at all in height until large root systems have formed.

Many species can be regenerated by vegetative sprouting which can be induced by cutting the parent trees and thus simulating natural tree killing by fire or animal browsing. Sprouting is common in angiosperms but only a few gymnosperms commonly regenerate from sprouts.

The sprouts usually arise from *dormant buds* that started as normal leaf buds but failed to develop. Instead they grow outward just under the bark, often for many years, and burst only when the crown of the tree is severed or becomes debilitated. *Stump sprouts* grow in rings around severed stumps.

In some species, such as aspen poplar and sweet gum, more uniformly spaced *root-suckers* arise from all parts of the root systems of the parents after they are cut or damaged. A few species can regenerate vegetatively from natural *layers* that are the rooted ends of branches that drooped down to the ground and were buried by litter or mosses.

Artificial regeneration can be accomplished by sowing seeds in the field or, much more commonly, by the planting of nursery-grown seedlings or cuttings.

C. Preparation of Sites for Regeneration

Treatments of soil or vegetation can sometimes facilitate the establishment of both artificial and natural regeneration. The treatments may involve use of fire, various kinds of plows and scarifiers, or herbicides. However, such site preparation is not always necessary for regeneration and can destroy advanced regeneration.

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The most common purpose is reduction of preexisting competing vegetation. This requires killing the roots of the unwanted plants. Mechanical action pulls them bodily out of the soil. Fire kills woody plants by heat-girdling which interrupts movement of sugar through the phloem to the roots. Herbicides kill either by similar girdling action or by translocation to roots. Flooding kills the roots by excluding oxygen from them.

Poorly drained soils can be aerated by plowing up ridges or *beds* on which seedlings can be established. Where hardpans impede internal drainage deep plowing can be used to break the pans. Sometimes wet areas with peat deposits are drained by use of elaborate canal systems.

At the other extreme shallow trenches may be created to collect water and improve survival of young trees planted in them. Irrigation of forest trees is possible but uncommon.

Sometimes exposure of mineral soil by scarification or burning of the litter layer is enough to improve germination of seed and survival of seedlings. Removal of organic litter improves upward and downward conductivity of the soil thus reducing damage from high temperatures or frost. Sometimes the litter of some species is *allelopathic* (i. e., chemically antagonistic) even to seedlings of the same species. Especially for small-seeded species, improved contact between the seed and denser water-supplying media is vital to germination.

Site preparation with machinery can harm the soil by excessive scraping, gouging, or packing. Much of the nutrient capital of the site is often in the litter. Therefore, any scraping action that moves litter more than a few feet to the side can impair soil fertility. Anything that impairs the porosity of the surface soil on slopes may cause accelerated erosion and stream siltation.

Fire is far less harmful because it leaves much more of the nutrient capital in place; some nitrogen and sulfur compounds may, however, be lost by volatilization. Oftentimes the burning of logging debris and the continuous blanket of fuel represented by leaf litter is important in reducing the hazard of fire in regions with long dry seasons.

Fertilization is one kind of soil treatment that is usually not necessary for the establishment of regeneration. Often it enhances the growth of weeds more than it does that of young trees. However, it may be necessary in the very early stages in cases with comparatively unusual nutrient deficiencies, especially those of phosphorus on poorly drained soils. The greatest benefits from fertilizing forest trees come after trees have become large enough to be laying down high-quality wood in the outer portions of their stems. In those circumstances and most others nitrogen compounds are the nutrients most likely to be deficient.

D. Artificial Regeneration

Artificial regeneration is usually accomplished by planting nursery-grown seedlings. *Direct seeding*, the sowing of seed directly in the forest, is successful only where seed predation by rodents and birds is avoided. It also requires rains frequent enough to keep the seeds wet. It is seldom feasible to apply the stupendous quantities of seeds that nature uses to overwhelm the appetites of the predators. Sometimes direct seeding works with species that have seeds so small that the predators ignore them. Otherwise direct seeding waits upon the invention of environmentally acceptable repellents of predators.

Planting evades many of the microenvironmental problems to which newly germinated seedlings are exposed in the field. The roots are put in contact with soil at depths from which water is not lost to direct evaporation. The top of the seedling also projects above the thin layer of air close to the surface that is subject to wide extremes of temperature. Enough environmental restrictions are evaded that it becomes possible to establish species or subspecies of trees in places where they could not become established in nature. This can be advantageous but also enables choices that can come to be mistakes.

The nursery practices used for forest trees are much like those employed for horticultural woody plants. They often involve techniques of forest tree genetic improvement (see below). [*See* Forest Tree, Genetic Improvement.]

Nursery-grown trees that are moved only once are called *seedlings*; those that are replanted one or more times in the nursery are *transplants*. The purpose of transplanting is to confine a large amount of root surface into a small volume and allow the top to grow larger before the plant goes to the field. The same purpose can be achieved by drawing knives beneath or beside the seedlings to prune the roots in place. The chief advantage of planting large stock is that the taller seedlings are more likely to overtop competing vegetation. There is, however, the risk that the roots, which are inevitably reduced in extent during planting, may not provide enough water for the leaves.

Nursery stock is sometimes grown from rooted vegetative cuttings. Cuttings of some species, mostly ones such as cottonwood poplars that normally grow along moist river banks, can be planted as unrooted cuttings directly in the field.

Nursery stock is planted either as *bare-rooted* or *containerized* plants. The bare-rooted ones are separated from the soil when lifted from the nursery beds; the containerized ones are planted with roots attached to the medium in which they grew.

It is easy to transport large numbers of bare-rooted seedlings to planting sites but success depends on meeting some restrictive requirements. The most important is the need for the seedling to reestablish contact between the root and the soil. Some of this can be accomplished initially by packing soil around the roots; however, it is more important that the planting be done just before or during a period in which the roots grow rapidly. Such periods usually occur at the beginning of the growing season and before leaf buds burst. Therefore, it is best to lift and move the seedlings late in their dormant season.

The roots will not grow unless the soil is moist. Sometimes there is a second period of root growth after that in which leaves and stems grow. However, success from planting then depends on getting enough root growth to supply the water that will be lost even during the dormant season.

Dormant bare-rooted plants can be kept in cold storage (above freezing). This may postpone the time of maximum root growth and extend the planting season. If there is no dormant season, as in species of tropical rain forest, bare-rooted plants survive only if planted within hours of lifting. The roots of any bare-rooted stock must be kept visibly moist at all times; freezing or air-drying before planting will kill them. The period during which this kind of planting can be done is often limited to a few frantic weeks.

Ordinarily the plants should be reestablished with their root-collars level with the soil surface as they were in the nursery, but better too deep than too shallow. The roots should extend downward vertically as deeply as possible and not be bent upward into shapes like the letters J or L. Despite all these limitations, bare-rooted planting is the most common mode of artificial regeneration.

Containerized planting is expensive but more dependable. The main advantage is that contact between the roots and the medium in which they grew is not broken. This means that the planting can be done whenever the soil is moist and unfrozen. It has always been the standard method of tree planting in the moist tropics where there is no dormant period and in arid regions where survival after planting is poor. The same is true of planting trees more than about a meter tall.

One problem with containers is that they can cause the roots to spiral around inside the container walls. In this "root-bound" condition root systems do not resume their normal radial growth. Therefore, seedlings cannot be left to grow very long in the containers and it best that the containers either be removed or ruptured severely before the plants are put into the soil. This problem can be avoided if the container is a block of some organic material and has no walls.

V. Tending of Established Stands

After stands of trees are well established it may be desirable to apply various treatments, sometimes called *intermediate cuttings*, to improve the crop but not to replace it. Usually they involve eliminating some trees to create vacancies in growing space into which favored trees can expand.

A. Releasing Operations

The species composition of new stands can seldom be perfectly controlled during the regeneration phase. It may be necessary to adjust this by eliminating plants that overtop the desirable ones or threaten to do so. This can be done by cutting the undesirable, although this may have to be repeated if the unwanted plants resprout. It is also possible to kill them by *girdling* in which the bark is removed or severed; this kills the roots by starving them of carbohydrates from the crowns.

Herbicides are usually more effective although they may have to be injected through the bark or specially formulated to penetrate the waxy coverings of leaves or bark. Foliage spraying, which can be done from the air, may be used to release narrow-leaved species, such as most conifers, from overtopping broadleaves, but the timing of such operations is crucial and variable. With foliage spraying it is necessary that the herbicide penetrate the leaves and then move to the rest of the plant, especially the roots. There are some herbicides sufficiently phytotoxic that they can leach down to the roots and kill them after applications to the soil surface.

Tending operations are *cleanings* if the desirables and undesirables are of equal age and *liberation operations* if the undesirables are older.

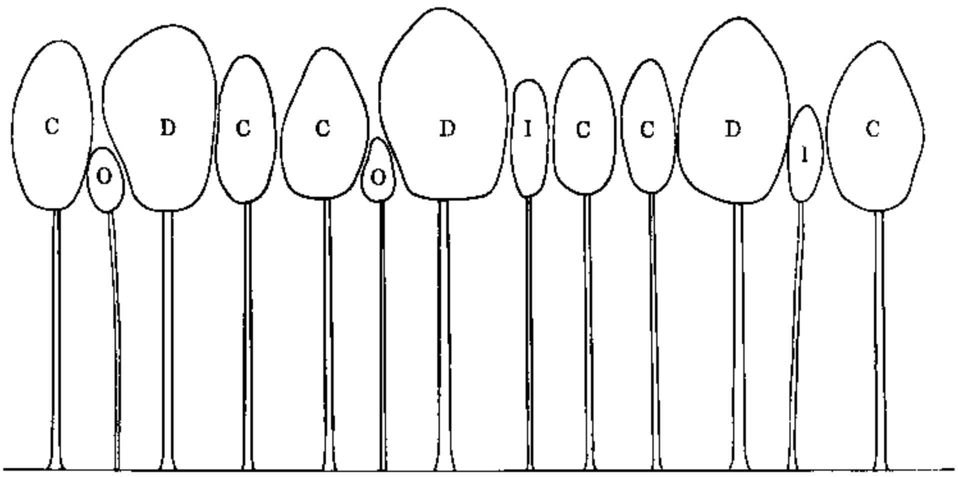

FIGURE 4 Relative positions of trees of different crown classes in a pure, even-aged stand. The letters, D, C, I, and O, stand for dominant, codominant, intermediate, and overtopped crown classes. [Reprinted with permission from Smith, D. M. (1986). "The Practice of Silviculture," Fig. 2-3, p. 47. Copyright © 1986 by John Wiley & Sons, Inc., New York.]

B. Prescribed Burning

Where the desirable trees have thick enough bark fires may periodically be set to burn the leaf litter and other fuels beneath the stands. The purposes may be (a) reduction of fuels in which wildfires might burn, (b) improvement of forage production for wild or domestic animals, (c) killing of small undesirable woody plants, (d) pest control, or (e) exposure of bare mineral soil to prepare for regeneration. Fire is most commonly prescribed where conditions are dry enough, at least seasonally, that fires often run under the stands in nature.

The weather and fuel-moisture conditions must be carefully chosen; the areas to be burned must be surrounded by plowed fire-lines or other belts from which the fuels have been removed at least temporarily. *Back-fires*, which are caused to burn against the wind move slowly but cause heat to be concentrated near the ground. *Head-fires* burn with the wind; much of their heat is wafted aloft where it may scorch some foliage but is less likely to scar the bases of the trees. Only *surface fires* which burn only the material on the forest floor are used. *Ground fires* which burn fuels underground and *crown fires* which burn both foliage on the trees *and* surface fuels are avoided because they are too difficult to control and too harmful.

C. Thinning

Forest stands start with many trees and then the numbers dwindle as the crowns of the more vigorous trees expand and shade out the losers. During this process the trees of a pure, even-aged stand differentiate into the *crown classes* depicted in Fig. 4. The leading trees or *dominants* have crowns free on all four sides.

Codominants are free on one to three sides. Trees that receive light only at their tops are of the *intermediate* crown class and are fast dropping out of the race for the sky. *Overtopped* trees are completely closed over and, at least if competing with the same species, doomed to early death. Figure 5 shows the process of differentiation into crown classes and the suppression of the laggards.

The diameters of the stems are closely correlated with those of the crowns and with the crown classes. The volume, value, and utility of the stem wood vary directly with the square of the diameter so small increases in diameter growth can be valuable. If the natural decline in numbers of trees is speeded by thinning both the tree crowns and the stems increase faster in diameter.

The diminution of numbers also means that some of the wood that has been produced will be lost to decay unless the doomed trees are harvested in thinnings. In this way the yield of wood from the stand is increased even though the total production of biomass is not. In fact, any temporary vacancies in the upper crown space created by thinning result in reductions of total biomass production. However, this sacrifice is deliberately made because the utilizable yield of wood in the larger stem sizes is increased.

The choices of trees cut and left in thinning also enables removal of poor or unhealthy trees to favor

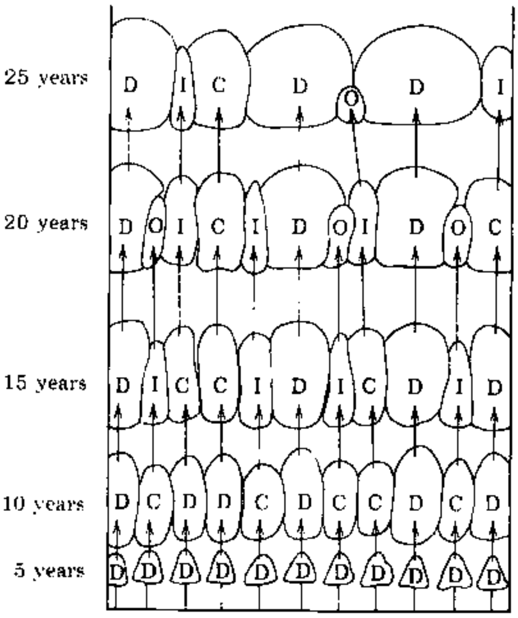

FIGURE 5 Changes in relative position in the crown canopy at successive ages as trees that all start as dominants race for the sky and some drop out. The letters refer to crown classes as in Fig. 4. [Reprinted with permission from Smith, D. M. (1986). "The Practice of Silviculture," Fig. 2-4, p. 48. Copyright © 1986 by John Wiley & Sons, Inc., New York.]

the growth of those of best quality or species. The increases in diameter growth caused by thinning are greatest at the base of the stem. This ultimately increases resistance to wind damage but requires several years of growth; until then thinning has the temporary effect of increasing vulnerability to wind.

The *methods of thinning*, which are patterns of choices of trees to cut and leave, vary with the objectives and the characteristics of the stands. Figure 6 illustrates how the different methods alter the distribution of classes of stem diameter.

Low thinning imitates and accelerates the natural decline in numbers of trees by removing the small ones that have crowns submerged in the lower levels of the crown canopy. It provides the best way of salvaging prospective mortality caused by competition. It does not enhance diameter growth of residual trees very much unless the removals are heavy enough to make some gaps at the top of the foliar canopy.

Crown thinning concentrates on removing those trees of the top of the canopy that are the most serious competitors of chosen trees for the final harvest. These chosen *crop trees* are usually from among the dominants; the ones that are removed come from the codominants, except that a few good codominants may be promoted to crop-tree status if they are of better quality than some dominants. The intermediate and overtopped trees are left; usually they are too small to be utilized but it is sometimes hoped that some will respond to the release and grow large enough later. Leaving small trees and lesser vegetation beneath the larger trees decreases the growth of the larger ones where soil moisture is a limiting factor.

Selection thinning or *thinning of dominants* involves removing the tallest and largest trees and the hope that the shorter ones will respond with good growth. Sometimes this is done when the dominant trees are misshapen or otherwise less desirable than some codominants. Sometimes it is nothing more than "*high-grading*" in which the biggest and best trees are cut leaving the stand stocked with poorer ones. If the residual trees are of shade-enduring species and are of good form this pattern of removals can give acceptable results.

Geometric or mechanical thinning involves removal of trees in rows, strips or patterns that leave trees at fixed spacing intervals without much attention to choices of individual trees to leave.

Free thinning is that which is not limited to any one of these methods but varies from spot to spot. It is commonly applied to mixtures of species but can be used in irregular pure stands.

Commercial thinning involves any one of the foregoing methods in which the wood is extracted from the stand and utilized. In *precommercial thinning* the trees that are eliminated are left to rot in the stand. It is often geometric thinning and frequently involves killing individual trees with injected herbicides.

The severity of removals of trees in thinnings is usually regulated by determining the amount of crown cover to be left. Since that is difficult to measure the *basal area per acre* is often used as a surrogate parameter. The basal area of a tree is its cross-sectional area at breast height (4.5 feet) and is well correlated with the crown diameter. The number of trees per acre is not a good parameter, except for precommerical thinning in young stands, because it has nothing to do with tree sizes.

It should be noted that these methods of thinning and the terminology of crown classes were devised for even-aged stands composed of only one species; they do not fit most mixtures of species. Sometimes each stratum of a stratified mixture can be regarded and thinned as if it were a separate stand, although each stratum is retarded in growth by any that are

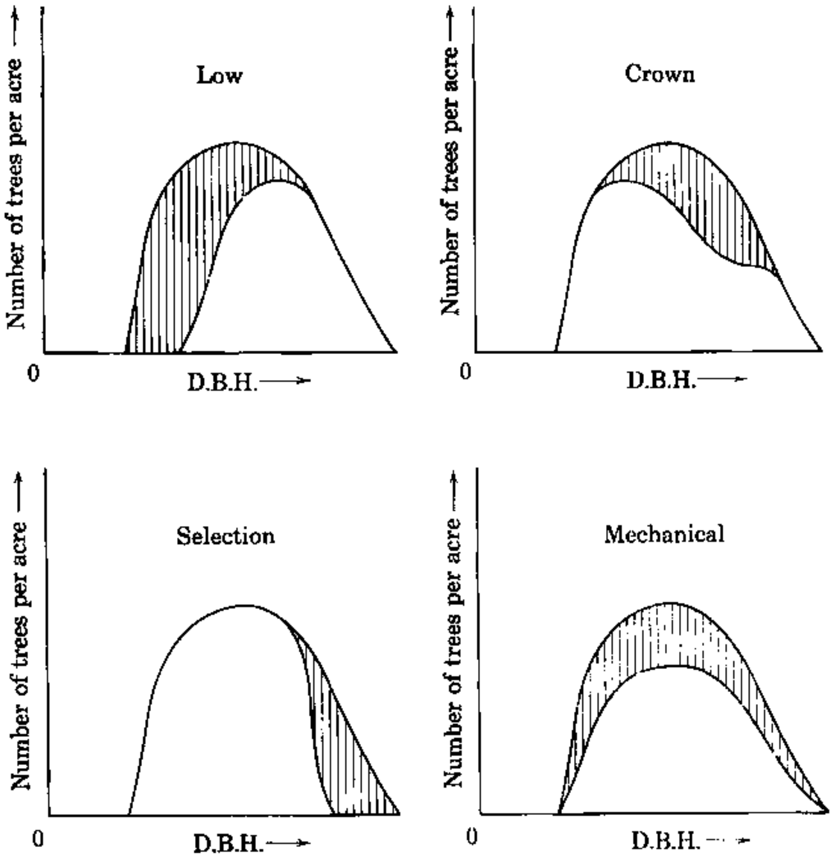

FIGURE 6 Diameter distributions for the same, pure, even-aged stand showing, by shading, the parts that would be removed in four different thinning methods. It is assumed that diameter at breast height (D.B.H.) is closely correlated with the crown classes. [Reprinted with permission from Smith, D. M. (1986). "The Practice of Silviculture," Fig. 4-11, p. 109. Copyright © 1986 by John Wiley & Sons, Inc., New York.]

above it. The difference is that the species of the lower strata are adapted to survive there.

D. Pruning

Trees cannot grow without branches but the branches may be detrimental after they die or even if they survive too low on the tree. Knots in boards are the remains of branches; they reduce the strength, utility and value of the lumber. Dead branches can also be infection courts for fungi or merely be unattractive. In growing trees for many purposes it is desirable to strike some desirable balance between the length of stem that is clothed with living branches and that which is free of branches. Knots left by dead branches are especially undesirable because they are apt to fall out when the lumber dries. The greater the proportion that is living the faster is the diameter growth of the stem.

A moderate amount of crowding in the early stages causes the lower branches to die when they are small. With many species small dead branches are attacked by wood-rotting fungi that cause the branches to fall off soon; fortunately these particular fungi are not the ones that can cause the heart of the tree to rot. However, this sort of *natural pruning* does not always take place. Furthermore, it is sometimes desirable to speed up the process by cutting off some living branches.

The most common purpose is to increase the proportion of knot-free lumber. It is often desirable to follow the pruning with heavy thinning so that the pruning wounds will heal swiftly and the trees will lay down knot-free wood rapidly. If too many live branches are removed, dormant buds along the pruned portion of the stem are likely to sprout and form new branches that defeat the purpose of the pruning.

VI. Silvicultural Planning

The growing of forest stands requires continuity of purpose and of treatment extending over many decades. The programs that are formulated to assure such continuity are *silvicultural systems.* They set forth the schedules of treatment planned for whole rotations. Usually one important part of the long-term plan is that it be reviewed and improved about once each decade. It is always necessary to keep looking at least one rotation ahead but to respond to changes in what is seen. The many considerations that enter into the plan generally conflict with each other so that each solution is a compromise.

A. Ownership Objectives

The natural conditions of each stand and forest govern the options available to the silviculturist but the objectives and characteristics of ownership come next in line. Helping ownership decide upon its objectives is often a major part of the formulation of a silvicultural system. This is especially true of public ownership where conflicts between groups seeking different kinds of benefits often keep the objectives confused and uncertain.

Such things as the choice of species to be grown depend heavily on how much of each kind of benefit is sought. The intensity of practice and degree of control of the vegetation depend on the capacity and willingness of ownership to make long-term investments in silvicultural treatment. The question of how long rotations should be partly depends upon ownership objectives. The result is that the optimum silvicultural program will not necessarily be the same for two different owners who have adjacent holdings of exactly the same kind of forest. For individuals the life expectancy is often a factor. Most important, however, is the relative importance attached to timber production, wildlife, watershed management, recreation and similar uses. Even then there is almost as much variation within categories as there is between them.

B. Control of Damaging Agencies

Trees must live through all seasons for many years in environments where it is not possible to afford them much protection. Control measures are *indirect* and *direct.* The general purpose is not to eliminate the sources of damage but to manage them in ways that make the damage tolerable or even advantageous for some purposes.

The indirect measure that is the first line of attack is silvicultural control which is maintaining stands with species, age classes, and overall structure that are not susceptible to damage. Much damage can be avoided simply by refraining from putting particular species on sites to which they are not adapted.

Sometimes the generalization is made that mixed, uneven-aged, stands of natural origin with vigorous fast-growing trees are most resistant to damage. While the various parts of this statement are singly more often true than not, exceptions are very numerous; the statement as a whole is probably more often false than true. The prospective damaging process must be analyzed and almost every general case treated differently.

Most of the control of fungus pests and abiotic agencies is silvicultural. Fungus spores are so omnipresent that fungicide use is usually confined to nurseries. Wind damage is best reduced by avoiding actions which create horizontal or vertical constrictions in the path of storm winds. That from frozen precipitation can be reduced by developing trees with symmetrical crowns and strong stems free of weak crotches.

Biological control, as in agriculture, involves use of the pests of pests. In forestry the most important application has been in the introduction of organisms that are enemies of introduced insects. The most effective predators of mammalian herbivore pests are hunters; fencing is feasible but very expensive. [*See* PEST MANAGEMENT, BIOLOGICAL CONTROL.]

Direct control with insecticides is applied mainly for control of outbreaks of defoliating insects and ordinarily involves aerial spraying.

Uncontrolled forest fires are incompatible with forestry; the section on Forest Fire Management deals with their control.

The final line of defense against sources of damage is the salvage of dead or dying trees, a purpose for which roads are very necessary. However, consideration must often be given to the role that dead trees, standing or fallen, play in wildlife management.

C. Sustained Yield

Forest production is one of the most truly sustainable of all human uses of resources. The fundamental basis of sustainability lies in maintaining the desirable physical and chemical properties of the soil. Where there is vegetative cover the large amounts of organic mat-

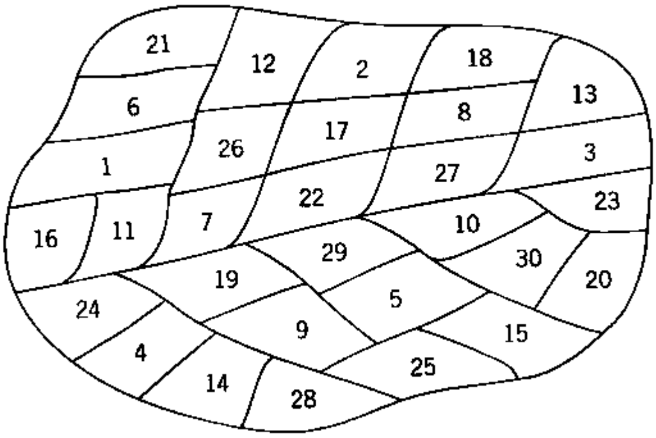

FIGURE 7 Schematic map of a forest divided into 30 equally productive stands arranged so that the replacement of one stand each year would provide a perpetual sustained yield of wood. Numbers denote stand ages, each of which is harvested at age 30. [Reprinted with permission from Smith, D. M. (1986). "The Practice of Silviculture," Fig. 12-2. p. 346. Copyright © 1986 by John Wiley & Sons, Inc., New York.]

ter that fall from the trees feed the soil organisms that keep the soil porous and resistant to surface erosion. The chief threat to forest soils is poor management of roads and trails; the actual cutting of trees and even fires have little effect.

The next consideration for sustainability is ensuring that stands are regenerated after timber harvests or similar disturbance.

The most difficult part of sustained yield is developing and maintaining some semblance of a steady flow of timber and other benefits from forests. The ideal in this respect is a *balanced distribution of age classes*, in which every age class from 1-year-old seedlings to that deemed mature is represented by an equally productive area of forest land (Fig.7).

If the mature age class is replaced with seedlings each year, there is theoretically an even flow of benefits that goes on forever. This kind of age class distribution is almost never created within single uneven-aged stands. The smallest administrative units for which it can be developed are whole forests consisting of thousands of acres. Even then the proper distribution is built through the course of many decades from even-aged stands. It is almost always necessary to have some age classes that have saleable timber but are not yet mature. True sustained yield depends on resisting all the temptations that exist to harvest such age classes prematurely.

It is very difficult to develop an appropriate range of age classes mainly because in most forest regions almost all of the stands are of essentially the same age when management starts. Sometimes most are beyond rotation age. In those cases it is necessary to replace a small area each year while most stands are kept to get even older and more decrepit. If the forests of a locality were all cut or destroyed at once there is often the problem that readjusting the age class distribution means cutting some stands when they are too young and leaving more to get too old.

Maintaining diversity of forest wildlife also depends on having a full range of age classes of stands. The actual ages need not be as precise but it may be desirable that some trees and stands be carried beyond the ages at which they would be regarded as mature from the timber standpoint. The kinds of species composition would also be more varied than those desired for timber production.

D. Optimizing Use of Capital and Growing Stock

The question of how long trees should be allowed to grow can be answered in part by assessing the compound interest return from two different kinds of investments made in the trees. The first is the return that trees earn on their own value and the second the return on the money invested in growing them.

In the first kind of analysis the value of the tree at the beginning of a given period of years is treated as an investment. The interest return on the investment is determined from the change in value of the tree that results from increase in size or quality. If the rate of return falls below that demanded by the owner–investor the tree is harvested. The same test applied collectively to all the trees of a stand may help determine rotation length. This mode of analysis often guides the choice of trees to harvest in thinning or other kinds of partial cutting. It also helps determine how heavy thinnings have to be to make trees grow fast enough to justify keeping them. With this method the rate of return earned by a tree is infinitely high on the first day it attains a positive financial value; it declines rapidly after that but can be made to increase again if the tree is made to grow fast and into sizes of high product value.

The second kind of analysis involves the rate of return on money actually invested in growing the tree. This method is chiefly useful for comparing different programs for growing stands of trees. The analysis is usually done by discounting estimates of all future costs and returns to the beginning of the rotation at the demanded rate of compound interest. The difference between the prospective costs and returns is the *present net value*. If it is positive this means that the proposed silvicultural system would earn the demanded rate; the present net value is what one could now afford to pay for the land under the trees.

These two financial tests are alternative methods; their interest rates are not additive. No analytical test of any sort takes everything into account. These financial tests are hard to apply to values other than timber. However, they can be very useful in formulating silvicultural systems.

E. Arrangement of Operations in Time and Space

Forests both as natural and administrative units spread over large areas of terrain. The pattern of their arrangement heavily depends on how the transportation network is arranged and maintained. This network is not limited to roads but may have to include the corridors along which some animal populations move. Some forest roads are kept open all the time and are used for many different purposes. Others are used temporarily and then best left closed and well drained until needed for the next operational entry.

Greatest operational efficiency usually results from maximum concentration of activity in space and time. At the extreme this would be achieved if all the trees of a large stand were cut and replaced during a single year and then left entirely alone until the next harvest at the end of the rotation. The other extreme would involve the intricate intermingling of trees of different ages and species with frequent silvicultural operations.

The most common compromise is keeping most stands essentially even-aged so that most treatments can be applied uniformly over the whole stand. Other considerations require that such stands not be unduly large. Among the logical criteria of stand size are (a) the operating radius of the equipment that first moves logs from the stand and (b) the extent of areas with the same kind of soil. It is also desirable to restrict the area covered by the activities of each year so as to limit the total length of road surface being disturbed at any one time.

VII. Silvicultural Systems and Their Application

The design of silvicultural systems for particular kinds of stands must be based on analysis of the foregoing considerations in the light of their relationship to given situations. It is fallacious in terms of economics, politics, and ecological science to accept the notion that any one universal system should prevail or that all are equally valid everywhere. Furthermore, there is much variation in the details of each category of systems. In fact the variable details are so important that none of the systems can be successfully applied as unvarying cookbook recipes followed without analysis of the particular cases at hand.

The regeneration step of a rotation-long silvicultural system is so crucial that the name of the *method of regeneration* is usually given to the whole system. These methods really describe the patterns of arrangement of cutting areas in space and time and only secondarily the sources of the regeneration. No system or method can be understood from the name alone; there must be further description of other details.

The methods (and systems) are initially categorized according to whether the regeneration comes primarily from (a) seeds or (b) vegetative sprouts. Within each category they are further subdivided as to whether the stands are even- or uneven-aged. There is terminology to indicate whether the cuttings are arranged (a) uniformly in space or are done in (b) strips or (c) groups and patches. An additional dimension is added for stratified mixtures of species in which individual species or groups thereof become segregated into different horizontal strata without necessarily being of different age.

There are three even-aged cutting methods in which reliance is placed on regeneration from seed: clearcutting, seed-tree cutting, and shelterwood cutting.

Clear-cutting, in the narrow silvicultural sense of the term, involves nearly complete removal of preexisting vegetation and reestablishment of a new one from planted seedlings or newly germinated seeds. It is most commonly carried out by heavy cutting, thorough site preparation, and planting of nursery-grown seedlings. The resulting plantations are usually pure but can also be of intermingled mixed species. With some species adapted to reseed areas after severe fires, the clear-cutting method can be made to work with natural or artificial seeding. The natural supplies of seeds that germinate after cutting may be stored in the soil or be dispersed by wind from adjacent stands. The term "clear-cutting" is often loosely used to refer to any form of heavy cutting regardless of whether or how a new stand is established.

Seed-tree cutting is the same as clear-cutting with thorough site preparation, except that trees left on the cutting area are the source of seeds. As is the case with other methods of cutting the pattern of application can leave trees in strips, groups, or as scattered individuals. The distances of effective dissemination are seldom more than three times the height of the seed trees.

In *shelterwood cutting* the renewal of the stand depends on advanced regeneration. Usually this is induced by a series or two or more partial cuttings in which enough trees are left on the site to provide seeds or partial shade. Emphasis is placed on creating vacancies in the growing space beneath the stand and admitting some sunlight to the forest floor. The trees that are reserved are generally the largest and fastest-growing of those in the stand; getting them to grow faster as a result of the heavy thinning effect is often part of the purpose of the treatment.

With the simplest form of shelterwood cutting the overstory trees are removed as soon as the new crop is well established. This creates the even-aged condition. However, in *irregular shelterwood cutting* the final removal cuttings may be postponed for many years or some of the smaller trees in the stand may be released and induced to resume rapid growth. This approach is best adapted to mixed stands in which different species do not grow at the same rate; new stands created by this approach are not perfectly even-aged. In cases where adequate advanced regeneration has already become established naturally it may be possible to create new stands with a single final-removal cutting of the old stand in "one-cut shelterwood cutting." While shelterwood cutting carries little risk of regeneration failure, there is no reason why the natural regeneration cannot be supplemented by artificial seeding or planting.

Uneven-aged stands are created and maintained by the *selection method of cutting* in which new age classes are established by removing trees in small patches or groups on three or more occasions during a rotation. Theoretically the same effect can be achieved by removing single large trees; however, the openings thus created are almost always so small that they are closed over by adjacent trees before any new trees can reach the top of the crown canopy. On the other hand the openings can be made large enough that it is possible to have uneven-aged stands that consist of groups of shade-bearing and even of sun-loving species.

The selection method is most commonly applied in stands that are already definitely uneven-aged and some trees would have to be harvested prematurely to make them even-aged. It also is applied in stands where it is desirable that there always be some large trees for such purposes as aesthetics, wildlife management, or protection against landslides and avalanches.

Theoretically the selection method can be applied in ways that mold each stand into a self-contained sustained-yield unit with the proper arrangement of age classes for that purpose. This is a goal that can be approached only very imperfectly. Sometimes there is the illusion of doing so in mixed stands in which tree diameter is taken as a good indicator of tree age, which it is not.

Unfortunately many sins are committed in the names of the selection method of regeneration and uneven-aged management, especially in mixed stands. It frequently degenerates into "high-grading" in which the biggest and best trees are removed from a stand often without actually making gaps large enough for truly new age classes to become established. It is often fallacious to assume that one can cut the big trees and expect the smaller ones to grow to replace them. The nontechnical term, "selective cutting," which denotes almost any kind of partial cutting, is sometimes a euphemism for high-grading.

The existence of two age classes in a stand is ordinarily a temporary condition. However, it can be a continuing one when there is reason to allow some trees of a stand to grow on rotation lengths at least twice as long as those of others. Usually this involves different species of differing longevity.

The *coppice* methods and systems depend on vegetative regeneration. The *simple coppice method* is the same as clearcutting except that the regeneration comes from sprouts, the surest mode of regeneration of all. It is by far the most ancient silvicultural method and has been used for millenia in Eurasia as a means of producing fuelwood and small poles. Cuttings at intervals of a few years repeated for centuries often induce clumps of sprouts so dense that the new trees are too feeble to stand straight or grow tall. This gave the coppice method a bad reputation. Much more recent experience in America has shown that trees of vegetative origin can be of good form if very short rotations are avoided. In fact, sprout regeneration is very important and useful in most forests of broadleaved species, including tropical rain forests.

One ancient variant of the coppice method is the *coppice-with-standards method* in which the basic coppice stand is regenerated frequently but scattered larger trees are carried for two or more coppice rotations. The purpose of this was usually to grow the small trees for fuelwood and the larger ones for construction material.

The methods of cutting applied in stratified mixtures usually involve thinking of each stratum separately. Each stratum can be thinned or otherwise treated as if it were a stand by itself. It is also possible by judicious removals in the upper strata to release trees of some (but not all) lower-stratum species to ascend into the top stratum. Regeneration is usually started as advanced regeneration by heavy removals of some of the lowermost strata in shelterwood cuttings. If it is later thoroughly released by removal of the upper strata the various species of the new stand gradually rearrange themselves into their respective strata.

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Soil, Acid

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Glossary

Buffered Buffered systems are able to resist change; soils are buffered against pH change by their ability to adsorb and desorb cations (+) including H^+ and Al^{3+}, at anionic (−) sites on their particle surfaces; buffered chemical solutions are also used in standardizing pH meters and estimating lime requirement of acid soils

Cation exchange Ability of soil to adsorb and desorb positively charged ions at negative sites on its particle surfaces; the capacity to adsorb cations is expressed in centimoles of charge that can be attracted per kilogram of soil

Cycle Carbon, nitrogen, and sulfur compounds each undergo modifications in nature that circulate them through various chemical states; carbon (e.g., as atmospheric CO_2) is reduced to -CHx forms in plants by photosynthesis; later it is returned to the atmosphere as organisms complete the cycle by oxidizing the plant residues back to CO_2

Nernst equation Equation relating the potential (voltage) produced by a specific ion electrode to the activity of the ion in solution; H^+ sensitive glass electrode of a pH meter produces 0.059 V change for each 1 unit pH change

Soil profile Vertical cross-section of the soil exhibiting the soil horizons (layers) which differ in physical or chemical properties

Soil taxonomy System of classifying soils derived for international use. It is analogous to the botanical classification of plants; soil order is the highest level of classification; all soils, based on chemical and physical properties, are assignable to 1 of the 11 soil orders (see the bibliography reference to Fanning and Fanning for more detail)

Acid soil has a pH of less than 7 on the 0–14 scale used to define acidity ($pH < 7$) and alkalinity ($pH > 7$). Acid soils have an excess of protons (H^+) over hydroxyls (OH^-) in their solution phase. This acidity produces increased solubility of metal compounds of iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), and aluminum (Al), with Al and Mn sometimes reaching levels that are phytotoxic. The proton and metal cation competition increases leaching of potassium (K), magnesium (Mg), and calcium (Ca) which may result in K and Mg deficiency and, in extreme cases, Ca deficiency. The cations which leach during acidification are accompanied by anions and thus acid soil may also be deficient in sulfur, boron, molybdenum, and phosphorus. For many plant species a slightly acid soil is the most desirable, but at a pH below about pH 5.5 many species begin to show adverse effects from the acid condition.

In this article the distribution and causes of soil acidity are followed by the soil chemistry of acidity, the nutritional and toxicity effects on plant growth, and the approaches to ameliorating and managing acid soils.

I. Location of Acid Soils

A. Geography and Climate

A major factor in production of acid soils is the naturally acidic rain which leaches the soil of salts, dis-

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Indiana Agricultural Experiment Station, Purdue Journal no. 13768.

solves the weatherable minerals, and removes alkali metal and alkaline earth cations from the soil. The replacement of the basic cations by protons from the rain then initiates the "acid soil" condition. Thus, acid soils occur in climatic zones where precipitation exceeds evapotranspiration for at least part of the year. High rainfall areas in the temperate, subtropical, and equatorial tropic zones have many regions of acid soils. The pH may be equally low in these three zones; however, subtropical and tropical soils are often more highly weathered due to higher temperatures, and thus show more auxillary or secondary effects of soil acidity. Strong acidity occurs in cool humid mountain ranges in most regions of the world. Significant acidity also exists where precipitation occurs as a short rainy season which exceeds the seasonal evaporative losses and causes leaching such as observed in Sahelian Africa. If regions where acidity exists, but is not severe enough to require amelioration, are included, then one notes that agricultural land of the earth is dominated by acid soils.

B. Taxonomic Classification

Soil taxonomy classifies all soils into 1 of 11 soil orders. Strong acidity occurs in the taxonomic orders of Spodosols, Ultisols, Oxisols, and Andisols. Most Histisols also are markedly acid but high pH seepage water from surrounding uplands causes some peat and muck soils to be near neutral as occurs where the uplands are formed from recent calcareous glacial till. Alfisols typically are acid but less severely so; this soil order requires >35% saturation of the exchange sites by basic cations in the diagnostic horizon. The developmental conditions necessary for Mollisols, Vertisols, and Aridisols generally exclude acidic soils from these orders. Finally, acidity in the soil orders of Entisols and Inceptisols is primarily dependent on the parent material pH and thus these soils can be either acid or alkaline. [*See* SOIL GENESIS, MORPHOLOGY, AND CLASSIFICATION.]

C. Within the Soil Profile

Acidity is not uniformly distributed vertically in the soil profile. Since acidity mainly enters soil at the surface from rainfall and other processes, one would expect the surface layer (A horizon) of a soil to be the most acid and lower horizons progressively less acid. This situation exists in some acid soils; however, many soils have a distinctive pH profile with the A horizon only slightly acid, the subsequent E and/or B horizon(s) moderately to strongly acid, and finally the deeper C horizon has the pH of the parent material. Nutrient recycling by plants and liming by man are mainly responsible for the less acid surface. Plant roots take large quantities of basic cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) from various depths within the soil profile and translocate them to the stem and leaf tissue. Roots absorbing these basic cations release an equivalent quantity of protons which acidify the root zone. Finally, with senescense or death, the stem and leaf tissue decomposes at the soil surface, releases the basic cations, and effectively relimes the surface. Figure 1 illustrates the effect of these processes in a profile view of unconsolidated calcareous parent material in a young, a mature (15,000 yr) and an old (>150,000 yr) soil, each receiving about 1 m of annual rainfall. As the acidification progresses, pH decreases and the percentage saturation of the cation exchange sites with acid increases. This process is even more extreme in very old, highly weathered soils (e.g., the Ultisols and Oxisols of high rainfall subtropical and tropical areas) where plant nutrition is often almost totally dependent on the recycled nutrients in the A horizon. Very little nutrition is retrievable from the acid subsoil, and the parent material is too deep for roots to benefit from basic cations in it. [*See* SOIL FERTILITY.]

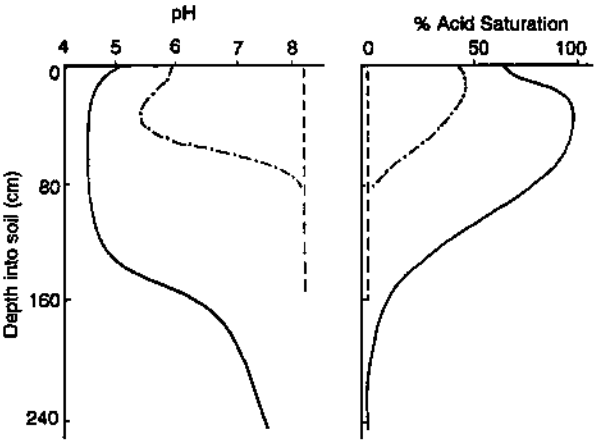

FIGURE 1 pH and percentage acid saturation in soils derived from unconsolidated calcareous parent material: young (Entisol), mature (Alfisol) and old (Ultisol) soils. ----, Entisol; —·—·—, Alfisol; ——, Ultisol.

II. Source of Acidity

Four atmospheric gases, carbon dioxide (CO_2), nitrogen (N_2), nitrogen oxides (NO_x), and sulfur dioxide (SO_2), via hydrolysis and/or redox reactions, are the primary sources of soil acidity. Atmospheric CO_2 and N_2 are major natural sinks for carbon and nitrogen. The CO_2, NO_x, and SO_2 all occur naturally, but are also industrial pollutants. [*See* SOIL CHEMISTRY; SOIL POLLUTION.]

CO_2, NO_x and SO_2 produce carbonic, nitric, and sulfuric acid (H_2CO_3, HNO_3 and H_2SO_4) upon further oxidation and/or reaction with water. In addition, living plants convert CO_2 and N_2 to the reduced forms of carbon and nitrogen ($-CH_x$, $-NH_x$) which predominate in living tissue. Subsequent oxidation of the plant residue introduces organic acids into the soil from the carbon and nitric acid from the nitrogen. The formation of reduced compounds typically results in proton consumption while oxidation releases protons. Reactions involving C, N, S, as well as Fe and Mn are major factors in acidification.

A. CO_2 and the Carbon Cycle

Rainwater in equilibrium with atmospheric CO_2, at its typical 30 Paschals partial pressure, has a pH near 5.6. However, the carbonic acid produced is a weak acid so the pH of the rainwater does not reflect the large quantity of undissociated carbonic acid that is also present. The magnitude of the acidifying effect is indicated by the calculation that 1 meter of annual rain at pH 5.6 should be able to dissolve 400–500 kg of $CaCO_3$ from a hectare of soil. A clear example of this is acidification in the eastern section of the glacial till plains of northcentral United States. The original coarse loamy till was 20 to 50% ground limestone rock and received an annual rainfall of about 1 m. These soils are leached of carbonates and acidified to a depth of nearly 1 m. About 5000 to 13,000 metric tons of carbonates per hectare have dissolved and leached over the 15,000 years since glaciation; an annual loss in the range of 350 to 880 kg ha^{-1}.

Some of the acidification by carbon is from the organic acids produced during decomposition of plant residue. If the decomposition occurs in somewhat anaerobic conditions, as exist in wet soils, then abundant simple organic acids are formed. The later stages of decomposition produce the rather stable black humus compounds common in surface soils. The main humus components are complex high-molecular-weight humic and slightly lower molecular weight fulvic acid. These all are carboxylic acids. The final oxidation of the carbon in soil organic matter produces carbonic acid at a high concentration in the soil solution because of the high partial pressure of CO_2 (5 to 20 times atmospheric) produced by this decomposition and by root and microbial respiration within the soil pores.

B. NOx and the Nitrogen Cycle

Acidification by nitrogen differs from that of carbon in that most plants do not directly use N_2 from the atmosphere. Thus, the main acidification by nitrogen is associated either with legume/*Rhizobium* symbiosis or with use of ammonium forms of nitrogen fertilizers [NH_3, $(NH_2)_2CO$, $(NH_4)_2SO_4$, NH_4NO_3]. [*See* NITROGEN CYCLING.]

In the legume/*Rhizobium* symbiosis the *Rhizobium* bacteria convert atmospheric N_2 to an $-NH$ or $-NH_2$ form that the host plant can use in protein synthesis. On death of the plant the decomposing tissue releases NH_4^+ which can nitrify and release protons to the soil.

$$NH_4^+ + 2\,O_2 \rightarrow NO_3^- + 2\,H^+ + H_2O.$$

Ammonium forms of nitrogen fertilizer undergo the same nitrifying process. This nitrification is actually a two-stage microbial oxidation from NH_4^+ to NO_2^- by *Nitrosomonas* species and on to NO_3^- by *Nitrobacter* species, but the two protons per NH_4^+ are released in the first stage.

Nitrogen fertilizer additions of up to several hundred kg ha^{-1} are often used on nonleguminous crops to provide the nutritional needs for nitrogen. This is the single most acidifying factor in many agricultural soils. Not all added NH_4^+ produce the theoretical two protons per ion since some NH_4^+ ions are taken up by plants before oxidation and secondary reactions may lessen the impact of others. Yet, the Association of Official Analytical Chemists (AOAC) procedure for neutralization of the acid produced by ammonium-type fertilizers recommends 1.8 kg $CaCO_3$ for each kilogram N added as ammonia or urea and 5.35 kg $CaCO_3$ per kilogram of N added as ammonium sulfate which is, respectively, 0.5 and 1.5 mol_c as $CaCO_3$ per mol N.

The contribution of atmospheric NO_x pollution to soil acidity is small. The nitric acid formed typically produces considerably less than 1 kg of H^+ per hectare per year. Since a hectare of soil 15 cm deep weighs about 2,000,000 kg, less than 0.5 ppm H^+ is being added annually to the tilled portion of the soil. The N added is useful as a nutrient, but it too is not very significant, generally less than 10 kg ha^{-1} $year^{-1}$.

C. SO_2 and the Sulfur Cycle

Elemental sulfur (S), protein sulfur (R-SH), and iron sulfides (FeS, Fe_3S_4 or FeS_2) are all reduced forms of sulfur. In each the sulfur will oxidize to sulfate and in the process release several hydrogen ions. Elemental sulfur is used to acidify soil especially when growing certain ornamental and crop species that are favored by more acid soil.

The reduced sulfur in plant and animal residues is mainly in two amino acids, cystine and methionine. The quantities of sulfur are small, usually about 0.3% in most tissue and thus contribute very little acidity during oxidation in the soil.

The major acidifying effect of sulfur occurs in isolated locations where iron sulfides have formed under special reducing conditions until large amounts have accumulated. When the environment then suddenly changes from reducing to oxidizing, sulfuric acid forms and a large amount of acidity is released. This oxidation occurs when certain coastal marshlands are drained, and where coal mine spoil or harbor dredgings are exposed to aeration. Some metal ores also exist as sulfides and mine spoil from the ore processing reacts like iron sulfide.

The iron sulfides form mainly in tidal marshes and ocean harbors. The marshes and harbors provide (1) a supply of sulfate and iron ions in the seawater, (2) adequate metabolizable organic matter as food both for the sulfate-reducing organisms and to maintain an anerobic system, plus (3) the flushing action of the tides to remove bicarbonates and to give partial oxidation, all of which combine to produce the correct environment. Sulfate then is reduced to sulfide and reacts with iron to form precipitates of FeS, Fe_3S_4 or FeS_2. These are black precipitates intermixed in the sediments of tidal marshes and harbors. Over geologic time iron sulfides have accumulated in coal, lignite, and sedimentary rocks and have often grown into larger, golden crystals of pyrite (fool's gold). The iron sulfides maintained under reducing conditions will not be acidic. Harbor dredgings often are black sediment with pH near 7. However, exposure to air rapidly produces sulfuric acid plus the sulfate and hydroxides of iron. The initial reaction of pyrite (FeS_2),

$$FeS_2 + 3\tfrac{1}{2}\,O_2 + H_2O \rightarrow FeSO_4 + H_2SO_4,$$

shows a mole of acid formed for each mole of pyrite. This can produce extreme acidity; the pH may be as low as 2. Extreme acidity in turn produces rapid weathering and many secondary reactions including formation of several ferrous and ferric iron minerals. The iron eventually becomes a ferric hydroxide precipitate, and a second mole of sulfuric acid is obtained from this hydrolysis of $FeSO_4$ to $Fe(OH)_3$.

In the atmosphere, SO_2 gas reacts with water and oxygen to give H_2SO_4. Like the HNO_3 produced from NO_x in the air, the SO_2, will produce a typical annual deposition of less than 1 kg H^+ per hectare. On a regional basis, in an industrialized country, the annual atmospheric acid deposition could be 1 kg of H^+ of which about one-third would be from NO_x and two-thirds from SO_2 reactions. In industrialized countries the sulfur in rainfall can easily equal 10 kg ha^{-1} $year^{-1}$ which fills a significant portion of the nutritional needs of plants for this nutrient.

III. Chemistry of Acid Soil

A. Clay and Humus as Acids and Acidic Soils

Soil acid is composed of an anion(−) and a cation (+). Typically, the anion is a mineral particle, one of the well-defined clay minerals, and may have from near zero to over 100 cmol of negative charge per kilogram of solid ($cmol_c\,kg^{-1}$). Partially decomposed organic tissue, humus, also is high in negative charge, up to 200 $cmol_c\,kg^{-1}$. These clay or humus anions are thus analogous to the immobile anion in a cation exchange resin. With H^+ as the exchangeable cation these immobile anions are true acids. Acid soil partially dissociates its H^+ to give an acidic solution. If, however, Al^{3+} is the cation on the clay or humus, it behaves as an acidic salt releasing Al^{3+} which reacts with H_2O (hydrolysis) to produce H^+ which acidifies the solution.

It is appropriate to note here that soil pH is a measure of the activity of the H^+ in solution (an intensity factor) and gives no quantitative indication of the amount of undissociated hydrogen or aluminum on the cation exchange sites of the soil (the quantity factor).

It is also important to realize that acidification requires leaching of the basic cations out of the soil upon displacement from the exchange sites by H^+ or Al^{3+}. The bases leach away, when rainfall is adequate, accompanied by the anions (e.g., HCO_3^- or NO_3^-) which were originally associated with the incoming acid.

Acid saturation differs between organic and mineral soils. Organic soils have carboxylate groups as the primary anion sites and the acid saturation can come from either Al or H, although H may predominate in the more purely organic soil. However, mineral soils most commonly have Al as their exchangeable acid cation on both their mineral and organic colloids.

The study of acid mineral soils thus is primarily a study of Al soils.

B. Acidity from Aluminum

Al^{3+} is a small ion with a high charge. This high-charge density gives Al a strong attraction for the oxygen of water molecules. Space around the Al ion permits coordination by the oxygens of six water molecules. The protons of water are repulsed by the close proximity to the trivalent Al and dissociate readily producing free protons (acidity) plus a series of hydrated Al–hydroxy compounds.

$$\begin{aligned} [Al(H_2O)_6]^{3+} &\rightarrow [Al(H_2O)_5(OH)]^{2+} + H^+ \\ &\rightarrow [Al(H_2O)_4(OH)_2]^+ + H^+ \\ &\rightarrow [Al(H_2O)_3(OH)_3]^0 + H^+ \\ &\rightarrow [Al(H_2O)_2(OH)_4]^- + H^+. \end{aligned}$$

As pH rises, the hydrated aluminum ion $[Al(H_2O)_6]^{+3}$ gives stepwise release of protons until Al finally appears as the anionic aluminate when pH is above 6.5. Figure 2 shows the pH effect on the general distribution of these ion forms (shown more simply without their hydrating water). In addition, $Al(H_2O)_5(OH)^{+2}$ ion can polymerize with others of its kind by sharing hydroxyl groups and thus produce Al species which are large, high-charge, polymeric cations. The Al–hydroxy compounds formed during hydrolysis are all quite stable (dissociate very little) and thus are very weak bases while the protons produced give a strongly acidic character to the system.

The Al ions come from dissolution of soil minerals. Aluminum is the third most abundant element in the earth's crust. It is present in many minerals where it is found surrounded by oxygen or hydroxyl in sixfold, and occasionally fourfold, coordination. Hydrogen entering the soil mineral dissolves Al by reacting with its coordinating oxygen or hydroxyl. The Al becomes $Al(H_2O)_6^{+3}$ or one of its soluble hydroxy ions upon dissolution while the proton becomes H_2O (a reverse of the type of reaction depicted in the equation above).

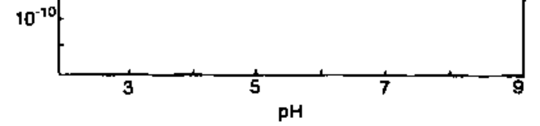

FIGURE 2 Activity of dominant Al species versus pH from gibbsite, $Al(OH)_3^0$, in equilibrium with water. [Adapted with permission from Lindsay, W. L. (1979). "Chemical Equilibria in Soils," Fig. 3.3, p. 40. Copyright © 1979 by John Wiley & Sons, Inc.]

C. Acid Soil, a Buffered System

Measuring soil pH gives only the hydrogen ion activity in the soil solution phase. Most acidity is stored on the colloid surfaces as exchangeable H^+ and as Al cations which hydrolize to produce H^+. The quantity of exchangeable acidity is commonly three to four orders of magnitude (1000 to 10,000×) greater than that in solution. When H^+ ion concentration in solution is reduced by addition of a base (e.g., liming), then either H^+ dissociates from the exchange sites to re-establish H ion concentration in the solution or more Al hydrolysis occurs to release additional H^+. In reverse, adding acid to a soil causes only small decreases in pH because most of the added protons react with the ion-exchange surface of the colloids and do not stay in solution. With a higher surface charge (higher cation exchange capacity) the soil has a greater buffering against pH change.

The greatest buffering occurs from the large permanent negative charge on most 2:1 lattice clays and from the variable (pH dependent) negative charge of carboxylate groups on soil humus. Some pH buffering also occurs in highly weathered soils low in 2:1 clays and organic humus. This buffering comes primarily from the ability of surface oxides and hydroxides of iron and aluminum to gain or lose protons (H^+) or hydroxyls (OH^-) as the H^+ activity in the solution phase increases or decreases. These oxide and hydroxide surfaces represent a type of variable charge surface. At the isoelectric point the surface absorbs equal amounts of H^+ and OH^- and has no net charge. If the pH of the isoelectric point is high, e.g., above 7, the surface will have a greater affinity for H^+ than for OH^- and vice versus. Thus, these surfaces develop a + or − charge which provides some pH buffering character.

Another type of buffering, long-term buffering, against acidification exists in soils which form from parent materials high in weatherable minerals: i.e., minerals which are relatively unstable in a humid climate. Weatherable minerals include carbonates, most

2 : 1 lattice clays, and such primary minerals as feldspars, feldspathoids, ferromagnesian minerals, and micas. Mg, Ca, K, and Na are significant components of such minerals. The H^+ in soil solution reacts with the carbonate, oxygen, and hydroxyl coordinating these basic ions, thus deactivating the H^+ and releasing the basic ions. This slows the soil acidification; however, eventually, the more weatherable minerals are depleted as in the Oxisols of the tropics. The soils then increasingly consist of the less weatherable 1 : 1 lattice clays, silica and iron, and aluminum oxides or oxyhydroxides and lose their large cation exchange capacity and most of the buffering associated with it.

As a result of the buffering, soils change pH very slowly. Thus, one would expect little or no measureable change in pH from an annual increment of acid rain, unless the soils had very low cation exchange capacities. Even high rates of acid-producing ammonical fertilizer should normally give only small annual pH changes in well buffered soils. The buffered character of soil, likewise, is active against attempts to raise soil pH. Liming an acid soil, if the soil is highly buffered, requires many tons of lime [$CaMg(CO_3)_2$] per hectare, and even on a poorly buffered soil a ton or two is required to significantly increase soil pH.

IV. Measuring Soil Acidity

Soil acidity is determined in two fundamentally different ways, a measure either of the H^+ in the soil solution or of the total (solution plus exchangeable) acidity in the system. The acidity in the soil solution controls the solubility of nutrient and nonnutrient ions and represents the acidity in which the plant roots and other soil organisms must live. It is often referred to as the "intensity" of the acidity. The total acidity, in contrast, represents that which must be considered in altering the acidity of the soil solution and is the "quantity" factor. [*See* SOIL TESTING FOR PLANT GROWTH AND SOIL FERTILITY.]

A. pH of Soil Solution

Soil solution acidity is measured in units of moles of H^+ per liter of solution. For convenience, these units are expressed as pH which is the negative log of the activity; thus, pH 5 is 10^{-5} mol liter^{-1} while pH 6 is 10^{-6} mol liter^{-1}. Each change of one pH unit represents a 10-fold change in H^+, e.g., a pH of 5 is 10 times more acid than pH 6.

pH is a measure of H^+ "activity," rather than "concentration"; however, activity and concentration are essentially equal when concentrations are low as they are in soil solution. As ionic strength of a solution increases, the H^+ activity will be somewhat less than concentration by an amount calculable by the Debye-Hueckel equation. In any case, the H^+ activity which the pH electrodes measure is the preferred information because activity, rather than concentration, determines the reactions in soil.

Soil solution pH is usually measured potentiometricaly with a glass electrode which is specific for H^+. As the H^+ activity in the soil suspension differs from the constant H^+ activity within the electrode, a potential is produced across the thin glass membrane. The potential is compared by the pH meter to a constant potential produced in a reference electrode which is also immersed in the soil suspension to complete the circuit, as shown in Fig. 3. The glass electrode responds according to the Nernst equation, which dictates that each 10-fold change in hydrogen ion activity should give a 59 mV change in potential. For use, the meter is standardized against solutions of known pH. The meter scale is labeled in pH units with one pH unit higher or lower for each 10-fold change in H^+ activity.

Soil solution consists of films of water adsorbed on soil particle surfaces and in the finer capillary pores. This is inadequate solution to give good contact with pH electrodes. Thus, solution pH is typically measured by adding distilled water, or a 0.01 *M* $CaCl_2$ solution to give a suspension of either a 1 : 1 or 2.5 : 1 solution to soil ratio. Adding distilled water dilutes the natural salts in the soil solution and tends to give an artificially higher pH rather than the true solution pH of an acid soil. The $CaCl_2$ solution attempts to maintain a salt content in the solution near that found in the original undiluted soil solution and thus gives

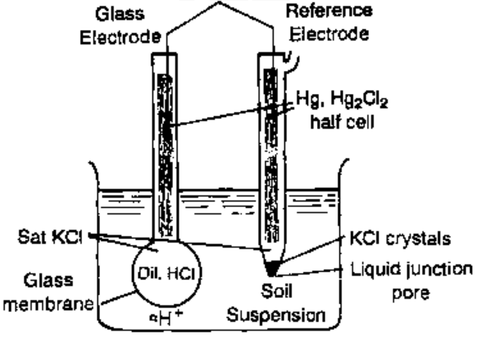

FIGURE 3 Glass electrode system for measurement of pH.

a slightly more valid pH. However, pH fluctuates within a field soil as salt and water content change with mineralization, evaporation, and rainfall; thus, either way of measuring pH can be valid for assessing soil solution acidity.

The pH can also be measured by equilibrating soil with solutions of certain organic acid indicators which change color as they go from associated to dissociated forms. Dilute solutions of the indicators are added to a small amount of soil in a spot plate and observed for indicator color change. Each indicator usually functions over a short range of less than 1 pH unit above and below its pKa. Commonly used indicators are Brom Cresol Green (pKa 4.6), Chlor Phenol Red (pKa 6.0), Brom Thymol Blue (pKa 6.6), and Brom Cresol Purple (pKa 6.0)

B. Total Soil Acidity

Total soil acidity is measured by displacement of cations from the soil with a salt solution and titration of the amount of acid present. Displacement by 1 *M* KCl gives the acidity that can be removed at the pH of the system because KCl is an unbuffered salt that immediately adjusts to the soil pH. Titration of the displaced acidity with a standard base then converts H^+ to H_2O and Al^{3+} to $Al(OH)_3$ and the hydroxyls consumed equal the total salt-exchangable acidity. Subsequent addition of a fluoride salt (KF) to the titrated solution causes F^- to displace the OH^- from the $Al(OH)_3$. The OH can then be titrated with standard acid (HCl) to determine how much of the acidity is attributable to Al.

A method of displacement with a solution of $BaCl_2$ buffered at pH 8.2 with triethanolamine is used to obtain total "potential" acidity. Buffering at pH 8.2 assures removal of acidity from weakly dissociating soil acids. This determination approximates the acidity that $CaCO_3$ in limestone can neutralize since saturated $CaCO_3$ solution has a pH near 8.2. It measures considerably more acidity than the KCl extraction, especially in acid soils that contain large amounts of humus and/or amorphous alumino-silicate material.

V. Acid Soil and Plant Nutrition

A. Direct Effects of Hydrogen

The effects of acid soil on plant growth are mostly secondary effects of the acid condition on the solubility of nutrient and nonnutrient ions and their availability to plants. The direct influence of the H^+ on plants is minor unless the pH is very low: pH 4 or less. It has been difficult to separate the hydrogen ion effect from the secondary effects associated with low pH.

B. Transition Metal Solubility

Increased solubility of the transition metals, Fe, Mn, Zn, and Cu, is generally a positive effect of an acid soil. In nonacid (alkaline or calcareous) soils deficiencies of these elements often occur because of the low solubility of their carbonate, hydroxide, and oxide forms.

C. Microorganism Activity

Acid soils reduce activity of most soil bacteria and actinomycetes. Thus, soil acidity can be used to control pH-sensitive disease organisms such as the potato scab organism which is controlled by keeping pH low. However, low pH also reduces microbial decomposition of plant residue. Since much of the N, P, and S needed by plants must be recycled from previous plant tissue, acid soil decreases the available N, P, and S supply. Also, some species of the symbiotic nitrogen-fixing organisms on legume roots (*Rhizobium* spp.) are sensitive enough to acidity (Al, H, low Ca) to result in nitrogen-deficient legumes on acid soils. [*See* SOIL MICROBIOLOGY.]

D. Phosphorus Solubility

Soil acidity can depress phosphorus availability in the natural situation because phosphorus forms low solubility salts with Fe, Mn, and Al. These three metal ions are much more abundant in acid soil solution than the meager supply of P, and therefore depress the quantity of P in solution. However, recent research indicates that soils that have had P added as fertilizer actually show greater P solubility in more acid soils.

E. Cation and Anion Leaching

Ions which leach are often in low supply in acid soil because acidity is mainly an artifact of long-term leaching. Thus K^+, Mg^{2+}, and Ca^{2+} can be reduced to deficiency levels by such leaching, augmented by their displacement from exchange sites by H^+ and Al^{3+}. Such deficiency occurs commonly in humid regions for K^+, less commonly for Mg^{2+}, and seldom for Ca^{2+}: in this order because of natural abundance and/or relative order of resistance to leaching. Leaching of Mn^{2+}, Zn^{2+}, and Cu^{2+} during soil acidification can cause deficiencies especially if followed by liming which decreases solubility of the small amounts of these three micronutrient metals remaining in the depleted soil. [*See* SOIL, CHEMICALS: MOVEMENT AND RETENTION.]

The anions (NO_3^-, SO_4^{2-}, and MoO_4^{2-}) leach readily because soils generally have little anion-exchange capacity. Boron, as H_3BO_3, has no charge and also leaches. Thus, acidic soils often are low in these nutrients. Interestingly, liming to raise the pH increases the MoO_4^{2-} in the solution often eliminating Mo deficiency; however, liming decreases solution H_3BO_3, accentuating B deficiency.

VI. Acid Soil Toxicity to Plants

Al and Mn, metal ions, reach toxic levels in some acid soils. Aluminum, a nonnutrient ion, has been most studied. Estimates of soil limitations to plant growth in the "developing" world show an average of 23% of the soil use is constrained by Al toxicity and another 16% limited by acidity without Al toxicity. Al toxicity is primarily due to the Al^{3+} ion species. Al^{3+} toxicity damages roots of sensitive species, an effect which occurs at concentrations below 2 μM liter^{-1} in solution culture. Yet soil solutions containing Al up to several hundred μM liter^{-1} may be either toxic or nontoxic. This ambiguity occurs because solution Al in soils occurs in many forms which are either nontoxic or less toxic than the Al^{3+} ion (e.g., $Al(OH)_2^+$, $Al(OH)^{2+}$, $Al(SO_4)^+$, and organic complexes of Al). Al toxicity is not expected in soils above pH 5.5 and seldom occurs until pH declines to <5.

Thus, without accurate speciation, it is difficult to know whether an acid soil will produce phytotoxicity from Al. Since accurate speciation is very difficult, a short-term bioassay with an aluminum-sensitive plant species gives the most efficient indicator of the toxicity. Roots in a toxic soil observed as soon as 2 to 3 days after germination are generally lacking in root hairs, much shorter, and may show spatulated root tips and necrotic tissue in comparison to those grown in a nontoxic check soil.

Toxicity of Mn is less common because Mn levels in soil are lower. Mn toxicity may be induced by a combination of high Mn content in the soil with low pH and/or reducing conditions which increase the solution concentration of Mn^{2+}, accompanied by an abundant supply of a nutrient anion like NO_3^- to stimulate cation uptake.

VII. Managing Acid Soils

A. Ameliorating the Soils

Soil acidity can be decreased or increased. Finely crushed limestone and marl are the most common products used to decrease acidity. Limestone and marl are available in most parts of the world and are easy to crush, thus making them inexpensive. Their primary ingredients are calcium and magnesium carbonate, two basic salts. Reacted with the soil solution they produce $Ca(OH)_2$ and $Mg(OH)_2$ which neutralize the acidity. Because of low solubility, the limestone must be finely crushed to expose a large surface area to the soil solution. The fine powder produced also provides adequate particles to permit good distribution, and thus uniform neutralization of acidity throughout the surface soil. Either calcium oxide or hydroxide (CaO or $Ca(OH)_2$) are occasionally used. Because they are manufactured from limestone they are more expensive; however, they have 179 and 136%, respectively, of the acid neutralizing value of calcium carbonate per unit weight. Other bases or basic salts also decrease acidity but generally are less available, less suitable, or more expensive. [*See* SOIL MANAGEMENT.]

Conversely, where a more acid soil is desired, elemental sulfur, an inexpensive yellow powder, can be added. It slowly oxidizes and hydrolyzes to sulfuric acid. A more expensive alternative which gives rapid acidification is the addition of the acid salts, ferrous sulfate ($FeSO_4$) or aluminum sulfate [$Al_2(SO_4)_3$], which form sulfuric acid upon hydrolysis. If one wishes to maintain or slowly increase acidity in soil, ammonium sulfate used as the nitrogen source for plants will accomplish this.

Liming an acid soil typically requires from 1 to as much as 20 tons of limestone per hectare. Prediction of the amount needed is based on determination of the acidity present by laboratory titration of the acidity of a sample of the soil: a slow process. More commonly, the amount needed is approximated by adding a measured sample of the soil to a standard solution which has been buffered at a rather high pH, e.g., 7.5 in the commonly used Shoemaker-McLean-Pratt (SMP) buffer solution. The acid soil decreases the pH of the buffer solution and this decrease has been calibrated to give the approximate lime needed to obtain the

TABLE I

Lime Required to Bring Soils to Desired pH as Determined by Equilibrium pH of SMP Buffer (pH 7.5) with Acid Soil

pH of soil–buffer mix	Desired soil pH[a]		
	7.0	6.5	6.0
6.8	2.5	2.0	1.8
6.7	4.0	3.6	3.0
6.6	5.4	4.5	3.8
6.5	7.0	5.8	4.7
6.4	9.0	7.6	6.3
6.3	10.5	9.0	7.4
6.2	12.1	10.3	8.3
6.1	13.4	11.2	9.2
6.0	15.2	12.8	10.5
5.9	17.2	14.6	11.9
5.8	18.6	15.7	12.8
5.7	20.2	17.0	13.9

[a] Values are tons pure $CaCO_3$/hectare to a depth of 20 cm. Adjust actual rate for quality of lime and depth of tillage.

desired soil pH as shown in Table I. The effect on soil acidity of adding limestone occurs over a period of a few months but should not need repeating for some years unless the soil has a very low cation-exchange capacity and large amounts of ammoniacal nitrogen fertilizer are being used.

Lime has little effect below the depth to which it is mixed. Thus, the subsoil will continue to be acid after liming. If the acidity inhibits deep and thorough root penetration, there will be inefficient use of soil water. Much of the drought stress observed in the southeastern United States and similar areas is probably induced by the adverse effect of subsoil acidity on root development.

B. Selecting Tolerant Species

Plant species differ in sensitivity to the elevated levels of aluminum, hydrogen, and manganese ions in acid soils. Pearl millet (*Pennisetum glaucum*) cowpea (*Vigna sinensis*), and cassava (*Manihot esculenta*) are examples of food species with great tolerance to acidity. In contrast, many edible beans (*Phaseolus vulgaris*), soybeans (*Glycine max*), and alfalfa (*Medicago sativa*) are examples of sensitive species. Variability in acid-soil tolerance within individual species also exists, and an acid tolerant variety or genotype will often grow well in a low pH soil where another variety of the same species does poorly. Plant breeders working especially with sorghum, forage legumes and grasses, wheat, and maize are evaluating their genetic material for acid/Al tolerance for use in producing varieties adapted to acid soil situations.

Thus, one can ameliorate a bad growth situation produced by acid soil by either amending the soil or selecting tolerant plant species or varieties. However, using plants with acid/Al tolerant roots will be important when liming materials are not available or too expensive and where acid subsoils are causing poor root development and drought stress.

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Soil and Land Use Surveys

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Glossary

Land Soil is one aspect of land; land concerns the complex of soil, vegetation, hydrology, climate, and infrastructure; much land is used by man for various purposes.

Land use Major kind of land use is a major subdivision of rural land use, such as rainfed agriculture, grassland, forestry or recreation; land utilization type is a kind of land use described or defined in a degree of greater detail than land use; it consists of a set of technical specifications in a given physical, economic, and social setting; terms multiple or compound land utilization types refer to situations in which more than one kind of land use is practiced within an area: a land use system.

Soil Collection of natural bodies on the earth's surface, in places modified or even made by man of earthy materials, containing mineral and living matter and supporting or capable of supporting plants out of doors; soils are classified according to systems such as the Soil Map of the World, the U. S. Soil Taxonomy and the French Soil Taxonomy.

Soil and land use surveys involve activities, which are intended to construct maps providing for the regional distribution of soils and land use. Different techniques are used for this purpose: (1) Field description and laboratory analysis of soils; (2) Land cover description and inquiries on land use; (3) Processing and interpretation of remote sensing imagery including aerial photography; and (4) Application of Geographic Information Systems (GIS).

I. Introduction

Soil maps are still needed in many countries. Many countries possess maps at a scale of 1:500,000 with information too broad to enable adequate planning of land use. For this a 1:100,000 soil map is a minimum requirement. After a first selection of promising areas, maps at larger scale (e.g., 1:25,000) provide definite lay out of parcels, drainage, and irrigation systems.

While soil may be regarded as a more or less stable feature with regard to the build up of the profile, the processes active in soil fauna, the distribution of salts and moisture, and the formation of soil structure are highly dynamic. One has to be aware of the fact that a soil map is not the final task of the soil survey. The same applies for land use: a highly dynamic feature. The mapping of land use may be done at a regular time basis. It is often aimed to characterize the process and indicate the causes for a change in land use, which can be socioeconomic or related to land degradation.

II. Soil Survey

Soils are surveyed in accordance to the physiography of the land. The latter may help in exploring the history of the land in a geological way (several millions of years) or in a human historical way (several hundreds and thousands of years). Both ways are important in defining "natural soil bodies" or cultural soil bodies, the latter entirely made up by human activity, e.g., soils with a plaggen epipedon produced by long and continued manuring. Different systems may be used in soil survey ranging from a grid system to a landscape-guided physiographic approach and the survey of key areas. In the latter, interpretation of aerial photographs and satellite imagery make it possible to extrapolate the results of well-defined soil surveys in relatively small areas.

The system used for physiographic interpretation of aerial photographs and other remote sensing imagery is illustrated in Fig. 1.

The resulting interpretation maps are used as an entry to plan the field survey, that is to locate the points, transects, and key areas to be surveyed. Field observations on soils, vegetation, land use, and relief provide the information required for locating boundaries between soil units, which can be checked for accuracy in a later stage. Grid surveys, or detailed observations in transects at relatively short distances, are generally used in detailed surveys at scales of 1:5000, where remote sensing imagery does not offer any key to soil distribution, where the soil landscapes are monotonous, or where statistical approaches to detect soil variability are intended.

Soil analyses are carried out for different purposes:

- To support the soil survey. That is, of different horizons in soil profile pits, a normal set of analyses involves the determination of soil texture, C, N, P, K, cation exchange capacity, exchangeable cations, base

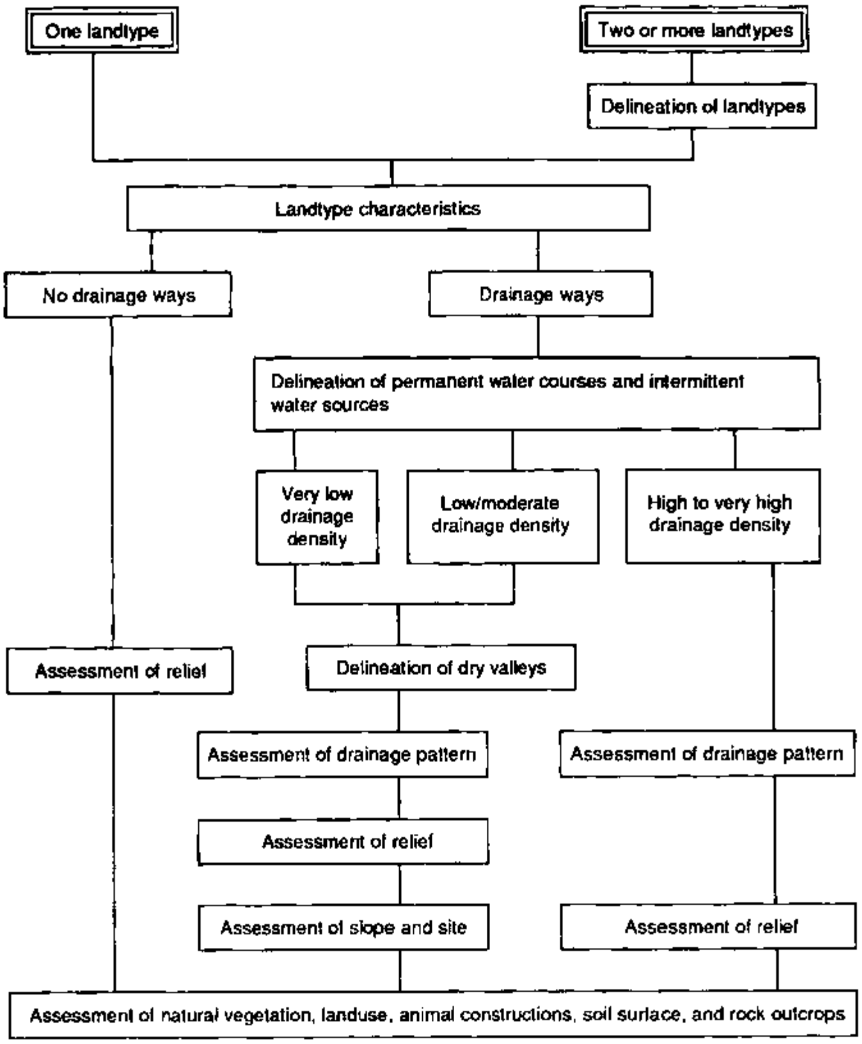


FIGURE 1 Physiographic interpretation for soil survey. [From Mulders, M. A. (1987). Remote sensing in soil science. *Dev. Soil Sci.* **15,** 379. Copyright Elsevier Science, Amsterdam.]

saturation, pH KCl, pH H_2O, and other data needed to characterize materials or soil horizons for soil classification.

- Samples at regular intervals to estimate salinity, that is by electrical conductivity and types of salts.
- To estimate soil fertility, that is besides N, P, and K, the exchangeable cations and trace elements (Cu, Zn, Mb, etc.).
- Physical measurements to estimate soil permeability and soil moisture availability.

Soils may be grouped in a number of sets according to the Soil Map of the World:

- organic soils or Histosols;
- mineral soils in which soil formation is conditioned by human influences—Anthrosols;
- mineral soils in which soil formation is conditioned by parent material—Andosols in volcanic material, Arenosols in residual and shifting sands, Vertisols in expanding clays;
- mineral soils in which soil formation is conditioned by physiography—Fluvisols and Gleysols in lowlands with flat to undulating relief, Leptosols and Regosols in elevated regions;
- mineral soils in which soil formation is conditioned by limited age—Cambisols;
- mineral soils in which soil formation is conditioned by climate and climate induced vegetation
  - –Plintosols, Ferralsols, Nitisols, Acrisols, Alisols, and Lixisols in tropical and subtropical regions
  - –Solonchaks, Solonetz, Gypsisols, and Calcisols in arid and semi-arid regions
  - –Kastanozems, Chernozems, Phaeozems, and Greyzems in steppes and steppic regions
  - –Luvisols, Podzoluvisols, Planosols, and Podzols in sub-humid forest and grassland regions

[*See* SOIL GENESIS, MORPHOLOGY, AND CLASSIFICATION; SOIL TESTING.]

III. Land Use Survey

A land use survey involves interpretation of aerial photographs and satellite imagery as well as terrain observations and inquiries on management and socio-economics. The definition of a land utilization type may involve management practices, crop types, and capital and labor inputs. A summary of the main land use systems is given below.

- Settlement/industries: residential use, industrial use, transport, recreational, and excavations
- Agriculture: annual field cropping, perennial field cropping, tree, and shrub cropping
- Animal husbandry: extensive grazing and intensive grazing
- Forestry: exploitation of natural forest and woodland, plantation forestry
- Mixed farming: agroforestry and agropastoralism
- Extraction/collecting: exploitation of natural vegetation, hunting, and fishing
- Nature protection: nature and game preservation, degradation control

Land use is often of a complex nature, for example: forestry and recreation in the same area or different agricultural activities on the same land. In Burkina Faso, sylvopastoral areas do not have clear-cut boundaries. These boundaries are vague, with sylvopastoral land only gradually changing into agricultural land. Furthermore, the use of the agricultural land is of a complex nature since sylvopastoral activities usually take place on these fields after harvesting. [*See* LAND USE PLANNING IN AGRICULTURE.]

IV. Application of Remote Sensing in Soil and Land Use Surveys

The information required for a soil survey involves a number of landscape attributes, such as relief, drainage system, natural vegetation, and land use (Fig. 1). The usual tool to gather this information is the stereoscopic interpretation of aerial photographs but other remote sensing techniques may be very helpful. These are:

- SLAR or side-looking airborne radar for small-scale analysis of vegetation, drainage systems, and relief
- MSS or multispectral scanning with Landsat MSS (80 m ground resolution), Landsat-TM (thematic mapper with 30 m ground resolution), and SPOT (*système probatoire d'observation de la terre* with multispectral and stereomode of 20 m ground resolution and a panchromatic mode of 10 m ground resolution). Apart from multispectral characterization of the land surface as used in medium- and small-scale mapping, these systems allow multitemporal observation of the land surface to study dynamic aspects: the relation with crop growth, development of natural vegetation, and soil moisture conditions is evident
- IRLS or (thermal) infrared line-scanning data are used for estimations on evapotranspiration and thus are valuable for waterbalance studies
- Multispectral aerial photographs at large-scale and different acquisitions throughout the growing season allow the accurate identification of crop types and the detection of growth differences within and between agricultural fields, thus serving studies on soil variability and fertility

Normally aerial photographs are used for survey purposes in combination with satellite data, the latter of most recent acquisition dates or spread out over a certain period of time to study changes of the land surface. Land surface properties are of equal interest to soil surveys and the survey of land use. The dynamics of the surface have to be translated into land use, using data such as provided for by crop calendars. The aerial photographs at large or medium scale generally provide those details, which help understanding of the small-scale information of the multispectral remote sensing tools.

Land cover describes the natural, vegetational, and man-made resources covering the land surface. It forms the basic output of the application of remote sensing for soil surveys and land use.

Three stages can be distinguished in land cover mapping using single-date Landsat thematic mapper data (TM):

1. Image processing in the prefieldwork stage focused on the overall variation of the scene
2. Small-scale reconnaissance fieldwork and processing thereafter, directed toward the production of thematic imagery
3. Medium-scale reconnaissance fieldwork and classification

These stages involve analyzing the digital datastructure of the remote sensing data (here: TM) as well as a structured method of field data sampling (Fig. 2).

As a first step in analyzing the digital structure, the digital numbers, the values assigned to the different TM wavelength bands, are processed according to selection criteria based on standard deviations and correlation coefficients. A three-band combination with the lowest correlation is composed. To indicate the variation of bands other than those selected by the former criteria, combinations of two or three principal components, expressing most of the variation contained in the TM bands (PC 1-2 or PC 1-2-3), are used.

In the field, the land cover types are identified and described, first sampled at small scale, and later on at medium scale, this latter after the inclusion of highly informative imagery showing variation within land cover class.

The final classification normally involves the inclusion of aerial photographic data besides TM data and training data (a combination of field data and classification results). Most of the land cover identification names have already sufficient detail to include them into land use systems; others have to be translated into land use terms using knowledge of the actual land use systems practiced in the area under consideration.

The scale and the physiognomy of the land use systems, the presence of parcel boundaries, etc., are important for the degree of detail. Figure 3 presents a TM image of an area in Costa Rica. The large parcels are identified without difficulty: banana in light grey; bamboo in grey.

Black and dark grey comprise natural forest while the irregular grey tone pattern mainly represents grassland.

Figures 4a and 4b are aerial photographs originally acquired at a scale of 1 : 50,000 (size 23 × 23 cm). Figure 4a represents an area with low annual rainfall in Burkina Faso (600 mm), where light-grey tones near valley bottoms and adjacent colluvial slopes indicate agricultural use (millet, sorghum, and peanuts); this in contrast to light-grey tones at the footslopes of ironcaps which have another meaning (discussed later). Parcel boundaries are absent or vague due to changing boundaries and the lack of permanent transport ways.

Figure 4b represents agricultural use in the same country but in an area with higher annual rainfall (900 mm) and ongoing agricultural development projects. Much of the area is occupied by a permanent lay out of parcels (with millet, sorghum, peanuts, cotton, and rice).

V. Matching Soil and Land Use

Experimental fields on which a specific land utilization type is practiced on a specific soil or soil association provide for quantitative data on technical and on economic aspects valid for that particular situation. The experiments can be used to define requirements of the land use, land qualities, and land suitability for that use. The method, which matches land and land use, is called land evaluation.

Most often, there are no experimental data available and information has to be collected by inquiries among farmers and interpretation of soil and climatic data.

Alternatives on this qualitative land evaluation are quantitative procedures, using a.o. simulation of the soil water regime to estimate the moisture supply capacity and estimates on the consumptive use of water by plants.

The latter is taken as an example for the soil and climatic data needed in quantitative land evaluation.

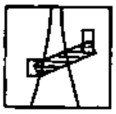
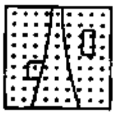
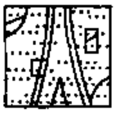
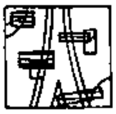
STAGE	INPUT SAMPLING	SCHEME	ACTIVITIES	SELECTION CRITERIA	OUTPUT
I.PREFIELDWORK STAGE AUTOMATED PROCESSING FOR PRODUCTION OF IMAGERY DIRECTED BY OVERALL VARIANCE		FIXED GRID 512*512 PIXELS SKIP FACTOR: 3	STATISTICS PER BAND MAXIMUM-MINIMUM FOR LINEAR STRETCHING		3-BAND IMAGERY USED FOR SELECTION OF TRAINING FIELDS
			STANDARD DEVIATIONS	HIGHEST VALUES	
		TRAINING FIELD 40*250 PIXELS	CORRELATION COEFFICIENTS BETWEEN BANDS	BANDS WITH LOWEST CORRELATION	3-BAND IMAGERY HIGH INFORMATION POTENTIAL
			AND		AND
		FIXED GRID 512*512 PIXELS SKIP FACTOR: 5	PRINCIPAL COMPONENT TRANSFORMATION	SUM OF VARIANCE	PC 1-2 OR 1-2-3 IMAGE
II. RECONNAISSANCE FIELDWORK SMALL SCALE 1:200,000 AND PRODUCTION OF IMAGERY WHICH IS OBJECT AND FEATURE DIRECTED	 SAMPLE SPOTS		FIELDWORK: IDENTIFICATION AND DESCRIPTION LAND COVER TYPES	VARIATION BETWEEN AND WITHIN LAND COVER TYPES	MAJOR LAND COVER CLASSES FOR FURTHER PROCESSING
		TRAINING FIELDS	AUTOMATED PROCESSING MAJOR LAND COVER CLASSES: MEAN VALUES AND STANDARD DEVIATIONS	SPECTRAL DISCRIMINATION BETWEEN CLASSES	3-BAND IMAGERY RATIO IMAGERY WITH HIGH CONTRAST BETWEEN CLASSES
			AND		AND
			WITHIN CLASS: PCT AND LINEAR STRETCH	IMAGE CONTRAST	IMAGERY WITH CONTRAST WITHIN CLASS
III. RECONNAISSANCE FIELDWORK MEDIUM SCALE 1:50,000 OR 1:100,000 AND CLASSIFICATION		SAMPLE SPOTS DIRECTED BY IMAGE DETAIL	FIELDWORK: ESTIMATION OF CAUSES OF DIFFERENCES BETWEEN AND WITHIN CLASSES	LAND COVER TYPES AND FEATURES OF INTEREST	LANDCOVER CLASSES AND RELEVANT FEATURES
			AUTOMATED PROCESSING SPECTRAL SIGNATURE FILES OF CLASSES AND FEATURES	MINIMUM DISTANCE MAXIMUM LIKELIHOOD, ETC.	CLASSIFIED LAND COVER CLASSES AND FEATURE IMAGE ACCURACY OF CLASSIFICATION
		SAMPLE AREAS	FIELDWORK: CHECK ON MEANING AND BOUNDARIES OF CLASSES SUPERVISED CLASSIFICATION	FIELD AND COMPUTER ACCURACY OF CLASSIFICATION	IMAGE AND LEGEND FINAL CLASSIFICATION

FIGURE 2 A structured approach in land cover mapping using single date Landsat Thematic Mapper data. [From Mulders, M. A., De Bruin, S., and Schuiling, B. P. (1992). *Int. J. Remote Sensing* 13(16), 3019–3036.]

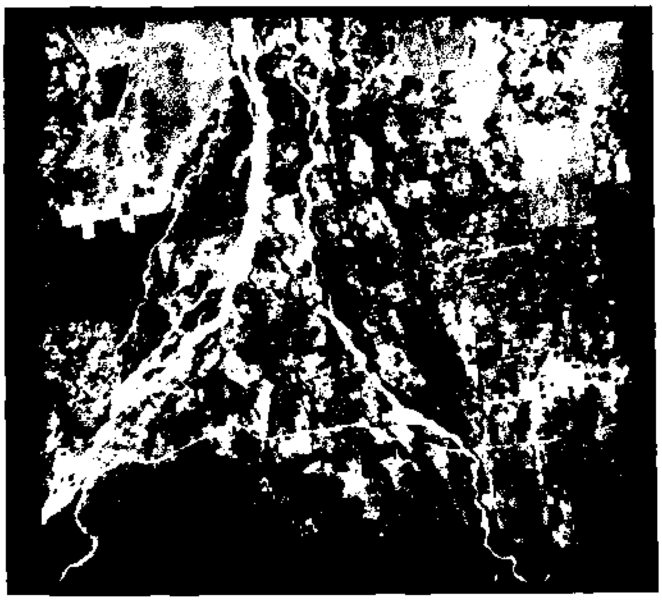


FIGURE 3 PC 1-2-3 combination of TM acquisition of 6 February 1986: Guapiles area in Costa Rica.

The maximum amount of available moisture that can be stored in the rooting zone can be defined by:

$$TASM = (SMFC - SMPWP) \times RD, \quad (1)$$

where TASM is the maximum possible amount of available moisture (cm)
SMFC is the volume fraction of moisture in soil at field capacity ($cm^3\ cm^{-3}$)
SMPWP is volume fraction of moisture at permanent wilting point ($cm^3\ cm^{-3}$)
RD is equivalent depth of a homogeneously rooted surface layer (cm).

The amount of moisture actually available for uptake at any moment (AASM) is defined by:

$$AASM = (SMPSI - SMPWP) \times RD, \quad (2)$$

where AASM is actual amount of available moisture (cm)
SMPSI is actual volume fraction of moisture in the root zone ($cm^3\ cm^{-3}$); Eq. (2) is valid if SMSPI is greater than SMPWP.

The compounded losses of water vapor from the rooted surface soil can be described for three ranges of soil moisture:

- if SMPSI ≥ SMCR (where SMCR is critical volume fraction of moisture in soil $cm^3\ cm^{-3}$, at which stomata start to close), water is consumed at the maximum rate (ETm = maximum rate of evapotranspiration cm d^{-1})
- if SMPSI drops to a value ≤ SMPWP, transpiration ceases; loss of water from the root zone is set at 0.05 × ETO (where ETO is potential rate of evapotranspiration cm d^{-1})
- if SMPWP < SMPSI < SMCR, the rate of loss of water from the rooted surface soil decreases proportionally to the decrease in moisture content, i.e., from ETm to 0.05 ETO.

This schematized ET-SMPSI relation is shown in Fig. 5.

The condition where SMPWP<SMPSI<SMCR is described by Eq. (3):

$$ET = (SMPSI - SMPWP) \times (ETm - 0.05 \times ETO)/(SMCR - SMPWP) + 0.05 \times ETO, \quad (3)$$

where ET is actual rate of evapotranspiration (cm d^{-1}).

For a dynamic analysis of land use systems, the following data are important:

- volume fractions of moisture in soil at field capacity and at pF = 4.2
- rates of precipitation and of potential evapotranspiration
- early mid-season stage of crop, duration of growing cycle, maximum rooting depth and the crop coefficient (relating the potential evapotranspiration with the maximum rate of evapotranspiration)
- initial volume fraction of moisture in soil, initial rooting depth and planting or sowing date.

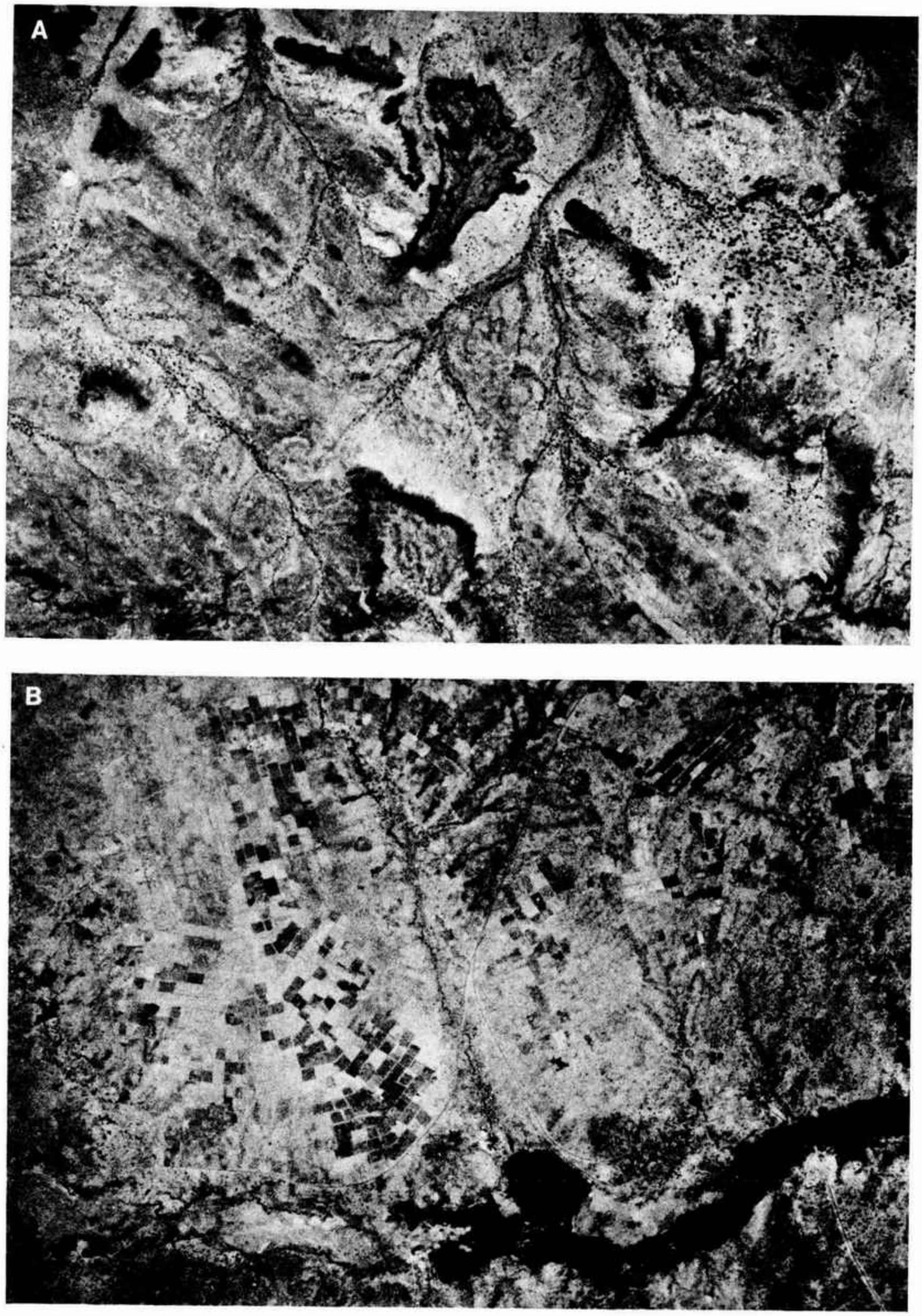


FIGURE 4 Aerial photographs of Burkina Faso. (a) Zablou area near Kaya; January 1982. (b) Kaibo area near Manga; January 1985.

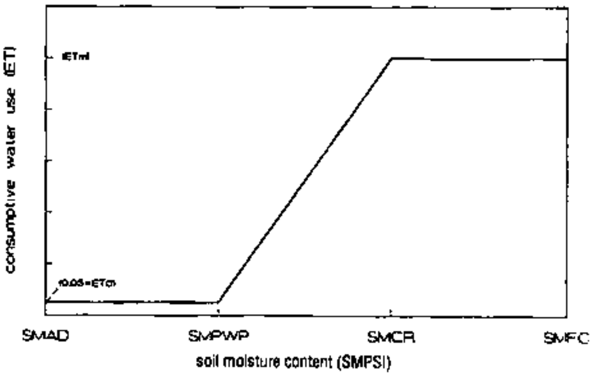


FIGURE 5 Approximate relation of ET to SMPSI. Abbreviations: see text. SMAD, volume fraction of moisture in soil at air dry condition (cm^3 cm^3). [From Driessen, P. M., and Konijn, N. T. (1992). "Land Use Systems Analysis." Wageningen Agricultural University, The Netherlands.]

VI. Land Degradation

Land evaluation is important for the selection of the most appropriate land use on particular land. If the land use is not in balance with the carrying capacity of soil or with that of natural vegetation, for example in case of natural grazing ground, it leads to land degradation. This can take place in many ways, for example, deterioration of soil structure (e.g., crusting and compaction), high soil salinity due to mismanagement in irrigation, truncation of soil profiles due to rain erosion and wind erosion, or the opposite namely accumulation of colluvial material, water transported materials and wind-blown sands.

Land degradation may be caused by remote activities, such as

- deforestation of watersheds causing problems in lowlands
- agricultural activities in areas with climatic drought leading to increased wind erosion and deposition in far away areas
- excess of gaseous waste in industries and of manure on agricultural lands causing sedimentation from polluted rain, which leads to an excess in soil nitrogen.

Some examples of land degradation are given below.

Figure 3 (Costa Rica) presents an example of replacement of tropical rainforest by banana, bamboo, and extensively used pasture. The economic value of the latter replacement is questionable and proceeds in a rapid and uncontrolled way.

Figure 4a is an example of degraded savanna in Burkina Faso.

The remaining trees are concentrated in the valley bottoms and where possible, agriculture is practiced. Lands exclusively used for pasture are the badlands with steep slopes (elongated hills) and ironcaps (dark grey features) as well as their stony footslopes. The scarce vegetation on the latter gives rise to accumulation of wind-blown sands and formation of low dunes (as apparent by white tones). Both Figures 4a and 4b show signs of accelerated water erosion. [*See* SOIL AND WATER MANAGEMENT AND CONSERVATION.]

VII. Geographic Information Systems (GIS)

GIS combines geographic data with the aid of computers. Different maps of terrain features may be constructed and combined to evaluate the coincidence or the absence of coincidence of boundaries.

Dbase is a computer program, which by sorting and comparing field data, evaluates the physiographic unit as a soil mapping unit and detects inaccuracies in the basic data.

Most of the aspects connected with soils and land use, such as land use requirements, land qualities for the intended use, and land degradation, have a complex nature. For example, to estimate land qualities, a number of relevant land characteristics are combined and weighted for this purpose. Such complex evaluations are served by the application of data bases and GIS.

As stated above, remote sensing data may be used to study dynamic aspects of the land surface. Figure 6 represents combinations of the TM bands 4, 5, and 3 at two dates of acquisition of the Kaibo area near Manga in Burkina Faso: 26 October 1989 (Fig. 6a) and 3 March 1987 (Fig. 6b).

October (Fig. 6a) marks the end of the rainy season; the dry period has started. Locally on the plateaux, crops still are green as evident by their medium greytones in the image. It indicates among others irrigated cotton. Furthermore, the agricultural areas with dry weeds and bare soil are visible in the image by white grey tones.

Figure 6b represents an image of March with in black the areas where burning of the savanna has been practiced.

The phytomass in this period is reduced considerably being limited to grass and shrubland on the plateaux and trees in the valley bottoms.

Such information on temporal changes in land surface features can serve land use and soil studies in an

FIGURE 6 TM imagery of Burkina Faso (Kaibo area). Acquisitions: 26 October 1989 (a) and 3 March 1987 (b). (a) white, bare soil and dry grass + weeds; light grey, dry grass, shrubs, and trees; grey, shrubs and trees with dry grass; dark grey, crops and abundant trees + shrubs; black, burned savanna area. (b) white, bare soil and dry grass + weeds; light grey, dry grass, shrubs, and trees; grey, shrubs and trees with dry grass; dark grey, abundant green trees in valley bottoms; black, burned savanna area.

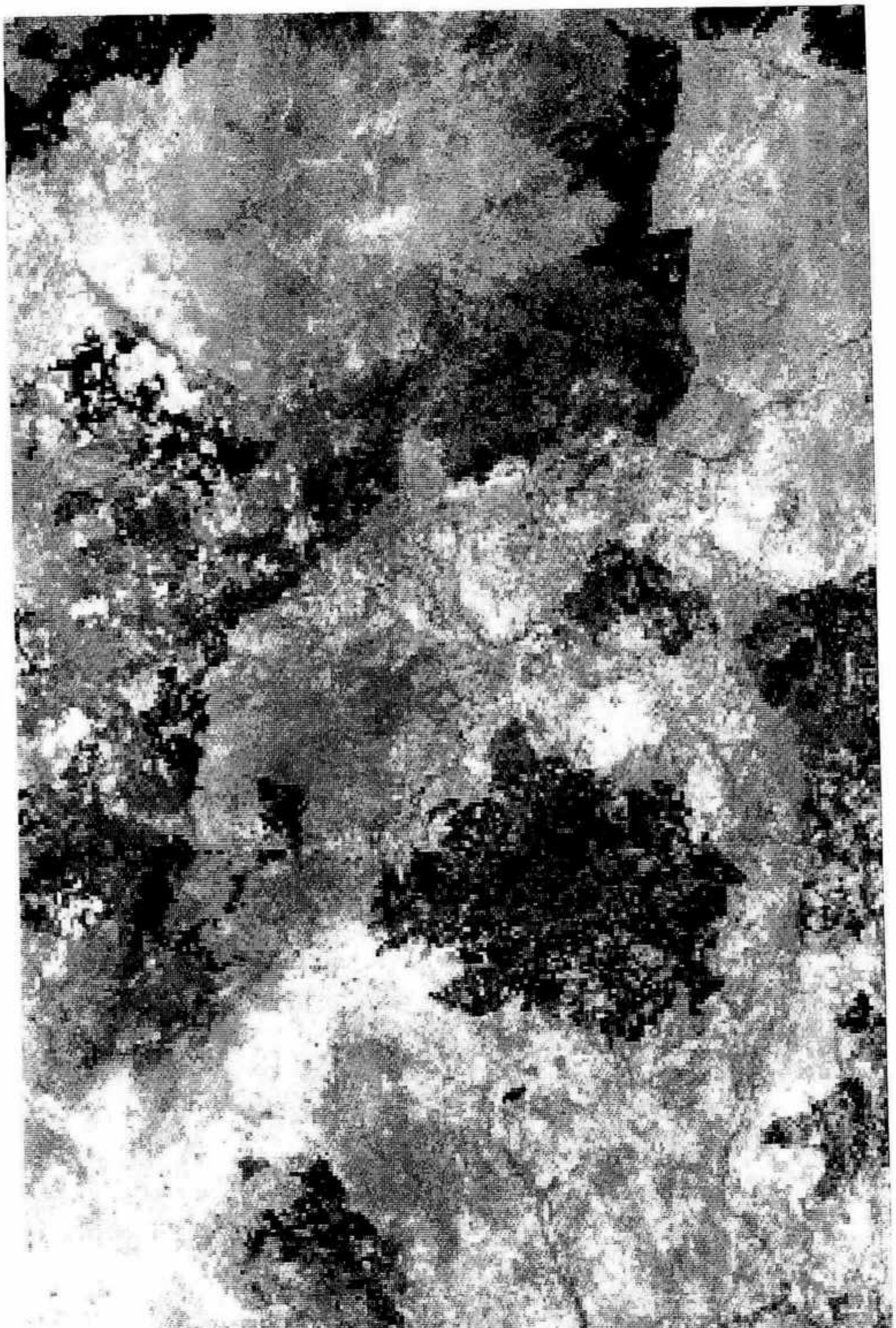


FIGURE 6 Continued

important way since it may be used to define the land surface dynamics. GIS is suitable for data handling and processing of products for interpretation.

The type of the basic data, which have to be collected for environmental studies considering the impact of man and biosphere, may be directed by those used in GLASSOD (Global Assessment of Soil Degradation). This project aims with SOTER (world Soils and Terrain digital data base) to define the input needed for calculating erosion factors and to evaluate erosion hazard on a regional and global base. Environmental data, such as climatic data, slope, soil, and crop coverage (as a protection factor), are regarded in this system and may also be applied at larger scales than originally intended.

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Soil and Water Management and Conservation

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Glossary

Anaerobiosis Excessive soil wetness due to poor or impeded drainage
Conservation tillage Methods of seed bed preparation designed to protect soil against erosion
Drought Inadequate water supply to plant roots
Infiltration capacity Rate of water entry into the soil
Mulch farming Soil management based on retention of crop residues and other biomass on soil surface
Runoff Overland flow caused by excessive precipitation
Salinization Buildup of salts in the root zone at concentrations toxic to plant growth
Soil conservation Protecting soil against agents of erosion
Soil erosion Soil displacement by water, wind, ice, or gravity
Terraces Channels constructed with earthen dikes down slope to intercept runoff

Soil, three dimensional upper surface of the earth crust in dynamic equilibrium with its environment and capable of supporting plant growth, needs to be managed on the basis of science-based inputs for enhanced and sustained agricultural production. Fresh water resources of the earth are also finite and limited. Adequate water availability is a major constraint for an intensive land use and increased agricultural production especially in semiarid and arid eco-regions. Therefore, soil and water management means judicious manipulation of soil and water resources to maintain and enhance their productive capacity and environmental regulatory functions. Principal among environmental regulatory functions are filtering pollutants from water, detoxification of industrial wastes, and regulation of gaseous concentrations in the atmosphere.

Conservation is a generic term. In a broad sense, it means preserving the resource base. In the context of soil, the term conservation means minimization of losses of soil due to accelerated erosion by water, wind, and other erosive agents. Conservation also implies enhancement of soil quality and productivity. In the context of water on agricultural land, conservation implies decreasing losses from the root zone due to surface runoff, deep seepage or evaporation. Conservation of soil and water resources is necessary for maintaining or enhancing their capacity to produce goods and services of economic, cultural, and aesthetic interests to humans.

I. Introduction

Soil resources of the world are finite, nonrenewable, and fragile. They are finite because potentially cultivable land resources are limited and unevenly distributed. Until about the 1970s, a considerable proportion of increase in food production was achieved by bringing new land under cultivation. However, reserves of potentially arable land are rapidly shrinking, especially in densely populated regions of the world. Furthermore, potentially arable land is either inaccessible, located in ecologically sensitive regions, or located in countries with robust economies. Densely populated regions of Asia and Europe have few additional lands to bring under cultivation. The per capita arable land area of the world has decreased from 0.32 ha in 1975

TABLE I

Per Capita Arable Land Area[a]

Region	Per capita arable land (ha)			
	1975	1980	1985	1990
Africa	0.368 (0.023)	0.326 (0.021)	0.288 (0.019)	0.254 (0.018)
America				
North Central	0.756 (0.066)	0.714 (0.074)	0.668 (0.069)	0.624 (0.062)
South	0.353 (0.029)	0.351 (0.030)	0.333 (0.029)	0.330 (0.030)
Asia	0.178 (0.052)	0.163 (0.051)	0.149 (0.050)	0.135 (0.048)
Europe	0.269 (0.027)	0.262 (0.030)	0.256 (0.033)	0.249 (0.034)
Oceania	2.046 (0.076)	1.949 (0.074)	1.920 (0.080)	1.834 (0.081)
USSR (Former)	0.895 (0.057)	0.857 (0.066)	0.822 (0.072)	0.779 (0.073)
World	0.321 (0.046)	0.298 (0.047)	0.276 (0.0465)	0.255 (0.0448)
Developed countries	0.574 (0.045)	0.556 (0.051)	0.540 (0.052)	0.519 (0.051)
Developing countries	0.223 (0.047)	0.206 (0.046)	0.189 (0.045)	0.173 (0.043)

[a] Calculated from population, arable land, and irrigated land statistics in FAO (1991). "Production Yearbok." Rome, Italy. Figures in parentheses are per capita irrigated land area.

to 0.25 ha in 1990 (Table I). In Asia, the per capita land area is only 0.14 ha with some countries having less than 0.1 ha. Average per capita irrigated land area is 0.07 ha in the world and that in Asia has steadily declined from 0.052 ha in 1975 to 0.048 ha in 1990 (Table I).

Soil resources are also nonrenewable at the human time scale. Under normal conditions, new soil is formed at the rate of about 2.5 cm in 150 to 1000 years. An exception to this rule may be the formation of soils in the flood plains or on the parent material of volcanic origin. Soils are also fragile to severe perturbations in harsh environments. Although most soils have built-in resilience, constant misuse and mismanagement can accentuate sensitivity to degradative processes. Soil degradation is a severe global problem especially in semi-arid and arid climates. As much as 38% of the arable land of the world is affected by some form of degradation (Table II). The per capita arable land area affected by degradation is about 0.1 ha out of the total per capita arable land of about 0.25 ha. At present 5 to 7 million ha of arable land (0.3–0.5%) is supposedly lost every year to soil degradation. The projected loss by the year 2000 is 10 million ha or 0.7% of the currently cultivated area. [*See* Soil Management; Soil Pollution.]

Despite these limitations of soil resources, the global agricultural production must be increased. An important strategy toward achieving this goal is proper use and science-based management of soil and water resources. In this regard, soil and water conservation and management play a crucial role in sustainable use of soil and water resources, decreasing degradation, restoring productivity of degraded resources, and maintaining or enhancing environmental quality.

The objective of this report is to describe basic principles of and technological options for soil and water management and conservation. The major emphasis is on addressing these problems on arable land with regards to water management, salinity control, and erosion management. These technological options are discussed in view of the global extent of the problems related to degradation of soil and water resources.

II. Water Management

Total global precipitation is estimated at 1130 mm/yr of which 233 mm or 20.6% falls on the land. Of the precipitation received on the land, 141 mm/yr accounts for evaporation or evapotranspiration and

TABLE II

Global Extent of Soil Degradation of Arable Land

Region	Degraded land		Per capita degraded land in 1990 (ha)
	Total (10^6 ha)[a]	% of arable land	
Africa	121	64.7	0.188
America			
Central	28	37.0	0.445
North	63	26.7	0.172
South	64	45.1	0.215
Asia	206	38.4	0.066
Europe	72	25.1	0.143
Oceania	8	16.3	0.296
World	562	38.1	0.106

[a] *Source*: Oldeman, L. R. (1992–1993). "Global Extent of Soil Degradation." Bi-Annual Report. ISRIC, Wageningen, The Netherlands.

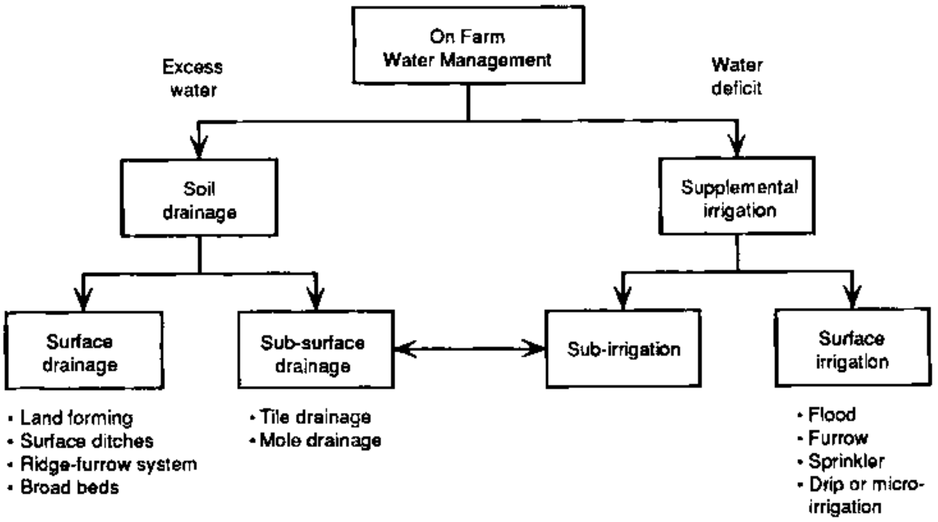

FIGURE 1 Technological options for on-farm water management involving drainage and supplementary irrigation.

the remaining 92 mm is returned to the ocean as surface runoff. Only 2.5% of the world's water is freshwater, and is an extremely scarce resource indeed. On-farm water management, crucial to sustained productivity and favorable environmental quality, involves drainage and irrigation (Fig. 1). Irrigation has played a major role in increasing world's food production since the 1940s. The world's irrigated land area has increased from 8 million ha in 1800 to 237 million in 1991 (Table III). In the United States irrigated land area was 8.3 million ha in 1944, 11.96 million ha in 1954, 14.98 million ha in 1964, 16.70 million ha in 1974, 20.38 million ha in 1978, and about 20 million ha in the 1980s. On a global scale, irrigated land accounts for only 16% of the cropland but produces 33% of the world's food. Management of irrigated land and water resources is, therefore, crucial to sustaining agricultural production. [*See* WATER: CONTROL AND USE; WATER RESOURCES.]

A. Improving Drainage and Reclaiming Salt-Affected Soils

Salt buildup in the surface layer is a natural phenomenon in soils of arid and semiarid regions with restricted drainage. In addition, mismanagement of irri-

TABLE III
Global Extent of Irrigated Land Area

	Irrigated land (10^6 ha)			
Region/continent	1975	1980	1985	1990
Africa	9.5	10.0 (5.3)	10.7 (7.0)	11.3 (5.6)
America				
North Central	22.9	27.7 (21.0)	27.6 (−0.4)	26.6 (−0.4)
South	6.3	7.2 (14.3)	7.9 (8.9)	8.8 (11.4)
Asia	121.7	132.4 (8.8)	141.2 (6.6)	150.2 (6.4)
Europe	12.7	14.5 (14.2)	16.0 (10.3)	17.1 (5.6)
Oceania	1.6	1.7 (6.3)	2.0 (17.6)	2.2 (10.0)
USSR (Former)	14.5	17.5 (20.7)	20.0 (14.3)	21.2 (6.0)
World	189.2	211.0 (11.5)	225.4 (6.8)	237.4 (5.3)
Developed countries	50.4	59.2 (17.5)	62.8 (6.1)	64.3 (2.4)
Developing countries	138.8	151.8 (9.4)	162.6 (7.1)	173.1 (6.5)

Source: Recalculated from FAO (1991); "Production Yearbook." Rome, Italy.
Note: Figures in parentheses refer to percentage increase over the past 5-year period.

gated water and misuse of irrigated lands can lead to two problems, e.g., salt buildup and poor drainage, soil wetness or anaerobiosis. Soils with toxic concentrations of soluble salts are widely distributed in arid and semi-arid regions and cover about 1 billion ha worldwide (Table IV). Total cropland and pasture land affected by salt buildup in the root zone in the United States is estimated at 225 million ha or about 9% of the total land in these categories. Unless properly managed, many irrigated lands are prone to salt buildup. Poor quality irrigation water is a major factor responsible for salt buildup. In addition to toxic concentrations of soils, an adverse consequence of high concentration of sodic salts in the root zone is the adverse effect on soil structure leading to restricted drainage and poor aeration. Rise in water table and poor drainage of the root zone are also caused by excessive seepage losses from unlined canals and delivery channels and low water use efficiency. Installation of artifical drainage can be expensive. It is estimated that about 44 million ha or 20% of the cropland in the United States required some drainage system by 1985 because of excessive wetness during early spring that delayed sowing operations. [*See* SOIL DRAINAGE; SOIL-WATER RELATIONSHIPS.]

B. Technological Options for Drainage

Provisions for drainage to remove excess water may preferably be made prior to planning for supplementary irrigation. Field drainage or farm drainage involves installation of techniques to remove excess water from a farm unit or part of the farm with localized problem of excess water. In contrast, land drainage involves installation of drainage network on a large scale to drain excess water from a large area. Drainage techniques described below refer to the field or farm drainage: Farm drainage is required for several reasons.

- Better drainage improves crop growth and yield. Increase in crop yield may be 5 to 20% depending on crop, soil, climate, and management.
- Improved drainage enhances nutrient use efficiency. Poor drainage conditions restrict availibility and uptake of several plant nutrients, e.g., N, P, K, Zn, Cu, B, etc.
- Drained soil has more favorable soil tilth and better soil physical properties than poorly drained soil.
- Trafficability is greatly enhanced with farm drainage and soil becomes accessible early in the season.
- Depending on the antecedent soil moisture content and microclimate, improved drainage may also warm up more quickly in the spring.
- Drained soils may also emit less greenhouse gases into the atmosphere than poorly drained soils, e.g., N_2O (Lal *et al.*, 1994).
- Drainage facilitates removal of excess salt from the root zone and is necessary to reclaim salt-affected soils.

Installing a drainage system, however, is a major capital investment. Furthermore, aging drainage systems are no longer effective and need replacement every 20 to 25 years.

There are two types of drainage systems (Fig. 1) Surface drainage, installed by a combination of land forming and open ditches, facilitates removal of surface water by land leveling and providing a gentle grade to speed-up the water movement. Surface drainage can also be provided through ridge-furrow system and by broad bed techniques of seedbed preparation. Open ditches are constructed to remove surplus water from the farm unit to the drainage way installed for the large area.

Heavy-textured soils require more than just the surface drainage to improve aeration conditions in the slowly permeable subsoil. Subsurface drainage is designed to regulate the groundwater table and consists of installing tube drains at about 50 cm depth. Spacing between the drain pipes depends on soil permeability, water table depth, and many other factors. Tube drains may be made of ceramic (tiles) or plastic. The gap between the two adjacent tiles or plastic drains, adjusted to facilitate free movement of water, is covered with a protective permeable fill or backfill.

One of the principal benefits of installing a drainage system is removal of excess salts from the root zone

TABLE IV
Global Extent of Salt-Affected Soils

Region	Area (m ha)	Irrigated land: Salt-affected soils (1990)
Africa	80.44	[illegible]
America		
Central and Mexico	1.97	
North	15.76	[illegible]
South	129.16	[illegible]
Asia		
North and Central	211.69	
South	[illegible]	
Southeast	[illegible]	[illegible]
Europe	[illegible]	[illegible]
Oceania	357.33	[illegible]
World	[illegible]	[illegible]

Source: Gupta, R. K., and Abrol, I. P. (1990). Salt-affected soils: Their reclamation and management for crop production. *Adv. Soil Sci.* **11**, 223–288.

of salt affected soils by repeated leaching with the drainage water. Leaching is often facilitated by application of farm yard manure, compost, green manure, gypsum, and other amendments. The problem of salt buildup and need for reclamation are particularly severe in irrigated regions of China, India, Pakistan, and the Middle East. Restoration of productivity of irrigated lands in these regions depends on provisions for proper drainage so that salts can be leached and kept out of the root zone.

C. Irrigation Techniques

Irrigation is the reverse of drainage because it implies application of water to the root zone to alleviate soil water deficit. Irrigation is used for several purposes but mainly to:

- Increase plant-available water reserves and decrease the risks of drought.
- Extend the growing season in regions with abrupt cessation of rains.
- Leach soluble salts out of the root zone in salt-affected soils.
- Regulate soil temperature especially for protecting sensitive plants from frost damage.
- Regulate nutrient supply to the root zone.

However, misuse of irrigation water can also lead to secondary problems with severe economic and ecological consequences. These problems include waterlogging and elevation of groundwater table, salt buildup in the root zone, decline in soil structure leading to crusting and slaking, and erosion of top soil especially in the furrow irrigation system. Adverse effects of irrigation on soil structure are related to water quality and composition of dissolved salts, e.g., Na, Ca, Mg, K, and the ratio of Na to other cations. Susceptibility to waterlogging and salinization in arid and semiarid regions also depend on the quantity and frequency of irrigation. Excessive application of water must be avoided, and irrigation water must be applied just enough to meet the crop water requirement. Crop water requirement depends on several factors including crop and soil types, climate, topography, etc.

On the basis of method of water application, there are two types of irrigation, e.g., subirrigation and surface irrigation (Fig. 1). The subirrigation method applies water to the root zone below the soil surface. In this method, the drainage system installed to remove surplus water is plugged and irrigation is applied through the same system. This is a cost-effective method with high water use efficiency and low evaporative losses. [*See* IRRIGATION ENGINEERING: FARM PRACTICES, METHODS, AND SYSTEMS.]

There are several methods of surface irrigation, the most common among these is the flood irrigation. This is the simplest method with least expenditure on equipment and storage. Surface irrigation is a natural system for semiaquatic crops (e.g., rice) and for large-scale reclamation of salt-affected soils by leaching. However, surface irrigation is an inefficient method with large losses due to evaporation. It also requires land forming and construction of several delivery channels. Efficiency of surface irrigation methods can be enhanced by using furrow rather than flood irrigation. A semi-permanent ridge-furrow system is a useful method for drainage in spring and for irrigation in summer. The ridge-furrow method of seed bed preparation is also useful for growing crops on salt-affected soils. While salt rises by evaporation to the ridge top, crops can be grown in the furrow or half-way up on the ridge to avoid salt injury.

Sprinkler irrigation system is the most capital-intensive but an efficient method in terms of water use. Principal advantages of sprinkler method include:

- Use on undulating terrain without prior land forming.
- Efficient water use because of low losses by seepage and poor delivery.
- Controlled application in terms of amount, and frequency.
- Flexibility in equipment use.

In addition to large capital investment, the timing of sprinkler application is affected by wind velocity. Structurally unstable soils can develop crust and surface seal due to impacting water drops.

Drip irrigation or microirrigation system is used to apply water at very low rates. The water is applied directly to the root zone of individual plants through a porous tube or especially designed emitters. Salt buildup is not a severe problem with drip irrigation. This system is extremely efficient because evaporative losses are reduced to the minimum. The system is also very effective in applying fertilizers and other chemicals directly to the root zone. However, the system requires a high capital investment and is feasible only for high value cash crops.

III. *In Situ* Conservation of Soil Water

In situ conservation of soil water, for minimization of losses due to runoff and evaporation, is extremely important to enhance productivity in rainfed agriculture.

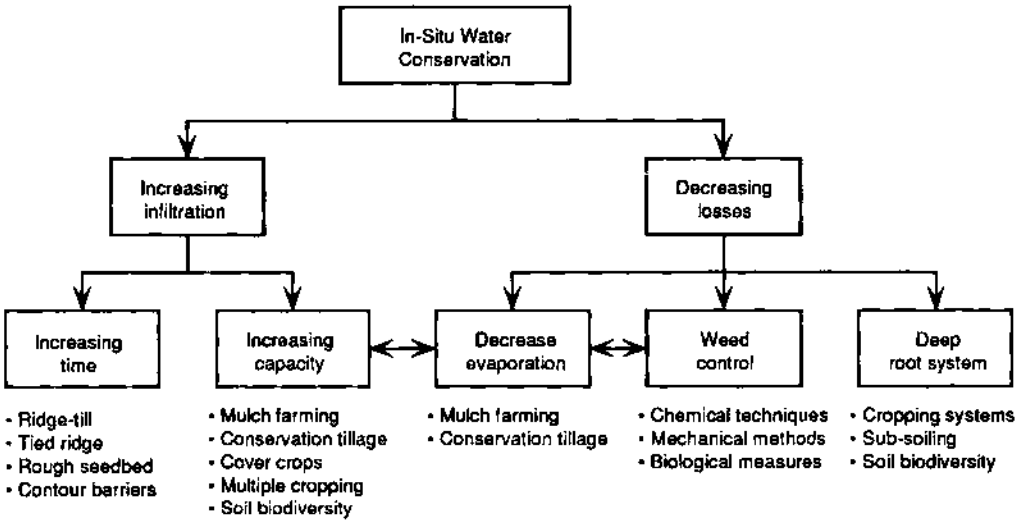

FIGURE 2 Strategies and techniques to improve *in situ* soil–water conservation.

Risks of drastic yield reductions due to drought in arid and semi-arid regions can be minimized through conservation of precipitation in the root zone. Techniques for *in situ* conservation of soil water are outlined in Fig. 2 and can be classified under two principal categories: (1) techniques to increase infiltration and reduce runoff losses, and (2) methods to decrease evaporation losses.

Losses due to surface runoff can be reduced by increasing the amount of precipitation infiltrating into the soil. The proportion of rain entering the soil can be enhanced by increasing the time for water to infiltrate or increasing soil's infiltration capacity. Increasing the time for water to infiltrate into the soil involves enhancing surface detention capacity through soil surface management or land forming. Commonly used techniques include rough seed bed, ridge-furrow system, and tied ridges (Fig. 2). Some of these techniques are described in the following section dealing with soil surface management. Contour barriers (e.g., bunds, vegetative hedges, etc.) are also used to contain runoff and allow it to infiltrate into the soil. Contour bunds create large storage to impound all the surface runoff and hold it for slow infiltration.

Evaporation losses are reduced by mulch farming and conservation tillage techniques. Mulches regulate the soil temperatures and decrease evaporation losses. These techniques are also described in the following section dealing with soil conservation.

IV. Soil Conservation

Accelerated soil erosion is a severe global problem, especially in ecologically sensitive ecoregions including the Himalayan–Tibetan ecosystem, the Andean region, the Caribbean, East African highlands, the loess region of China, and other steep lands in harsh climates. Wind erosion is severe in arid and semiarid climates. The data in Table V show that globally land area affected is about 56% by water erosion and 28% by wind erosion. Water erosion is severe in steep lands. Global distribution of steep lands include 3.3 billion ha with slopes ranging from 0 to 8%, 2.1 billion ha with slope of 8 to 30%, and 1.0 billion ha with slopes in excess of 30%. The largest areas affected by water and wind erosion are in Asia followed by that in Africa.

Accelerated soil erosion is also a serious problem in the United States. Land area affected is estimated

TABLE V
Global Extent of Water and Wind Erosion

	Water erosion		Wind erosion	
Region	Total (10^6 ha)	% of soils affected	Total (10^6 ha)	% of soils affected
Africa	227	46	186	38
America				
Central	46	74	5	7
North	60	63	35	36
South	123	51	42	17
Asia	441	59	222	30
Europe	114	52	42	19
Oceania	83	81	16	16
World	1094	56	548	28

Source: Modified from Oldeman, L. R. (1992–1993). "Global Extent of Soil Degredation." Bi-Annual Report, ISRIC, Wageningen, The Netherlands.

TABLE VI
Soil Erosion Hazard in the United States

Land use	Total area	Erosion hazard (10^6 ha)		
		<T[a]	Sheet and rill	Wind
Crop land	170.4	100.4	42.9	27.1
Pasture land	54.3	49.4	4.5	0.4
Range land	162.7	134.0	20.6	8.1
Forest land	159.5	149.8	9.3	0.4
Minor land	24.2	20.2	3.2	0.8
Total nonfederal rural land	571.1	453.8	80.5	36.8

Source: Modified from USDA (1989). "The Second RCA Appraisal: Soil, Water, and Related Resources on Non-federal Land in the United States, Analysis of Conditions and Trends," Washington, DC.

[a] T, tolerable level of soil erosion.

at about 81 million ha by sheet and rill erosion, and 37 million ha by wind erosion (Table VI). Some regions are affected by both water and wind erosion.

Principles of erosion control are well understood. However, techniques for erosion management are locale specific and vary with climate, terrain, land use, soil type, and other socio-economic and cultural factors. Erosion management techniques can be broadly grouped into three categories: (a) soil surface management, (b) slope management, and (c) runoff management. Basic principles of these techniques are briefly outlined below.

A. Soil Surface Management

Tillage and crop residue management are the principal tools of soil surface management for seed bed preparation, water conservation, and erosion control. In addition to seed bed preparation, an objective of soil surface management is to reduce or minimize risks of soil erosion by decreasing the aggressivity of agents of erosion, e.g., raindrop, overland flow, wind velocity. Basic principles of soil surface management through tillage are outlined in Fig. 3. In comparison with traditional (local methods) and conventional tillage (plow-based methods involving soil inversion), conservation tillage systems are designed to minimize soil erosion risks by decreasing exposure of the soil surface to climatic elements, through retention of crop residue mulch, and reduction in soil disturbance. Different types of conservation tillage systems are briefly discussed below. [*See* TILLAGE SYSTEMS.]

1. Conservation Tillage

It refers to some form of noninversion tillage with at least 30% of the soil surface covered with crop residue mulch. There are three principal types of conservation tillage: mulch tillage, reduced tillage and ridge tillage system. A classification scheme of conservation tillage is shown in Fig. 3.

a. Mulch Tillage Mulch tillage is any tillage system that retains a high percentage of crop residue on the soil surface. This system is also called stubble mulch tillage, mulch farming, trash farming, subsurface tillage, and plowless farming. There are two additional variants of mulch tillage. Sod seeding refers to the tillage system where crop is seeded directly in unplowed soil with chemically killed sod, weeds, cover crops, or previous crop residue. Contact or systemic herbicides (e.g., Paraquat or glyphosate) are used to replace plowing to kill vegetative growth. Sometimes a cover crop, usually a legume, is specifically grown to procure mulch, improve soil fertility, and enhance soil structure. This system is also called planted fallow or eco-fallow. In contrast, a cropless and weed-free fallow is used in arid climates to conserve water in the root zone. When a food crop is grown through the low-growing cover crop, the system is called live mulch. A live mulch system is based on the principle of mixed cropping in which a fast-growing and aggressive legume is established to smother weeds and then grow a seasonal food crop through it. It is usual to mechanically open a small strip, with or without herbicides, to establish the food crop. The live mulch system is effective only if the cover crop is a low-growing, nonclimber, and has a shallow root system.

b. Reduced Tillage Reduced tillage is a generic term which refers to reduction in intensity and/or

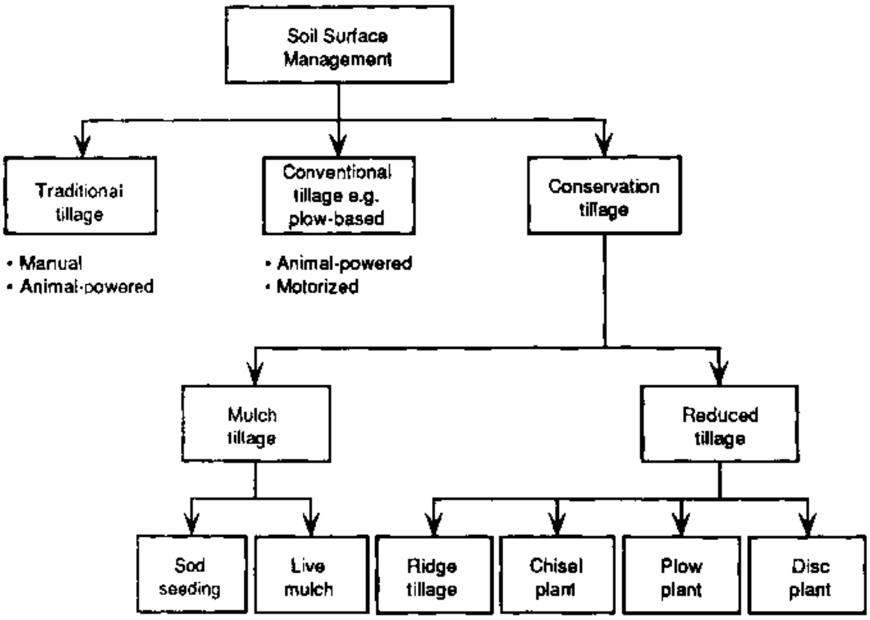

FIGURE 3 Soil surface management techniques for soil and water conservation.

frequency of mechanical or plow-based tillage systems. The most widely practiced form of reduced tillage is the no-tillage system in which all preplanting seed bed preparation is eliminated. This system is also called direct drilling or zero-tillage. In this system, all crop residue is left on the soil surface. Other commonly used variants of reduced tillage include chisel plant, plow plant, or disk plant depending on the equipment used to prepare seed bed prior to seeding.

2. Ridge Tillage

Ridge tillage involves heaping up the surface soil in a series of raised beds at regular intervals. Ridge tillage is a very versatile form of reduced tillage system. Ridges are made on the contour to contain runoff on soils of low permeability, up and down the slope on poorly drained soils to improve surface drainage, widely spaced and large to increase rooting depth on shallow soils, and to concentrate soil fertility by heaping up the nutrient-rich top soil in the root zone in subsistence farming or low-input systems. Ridges can be made every season, every other season, or with cross-ties (tied ridge system) to create a series of basins to increase water storage capacity.

3. Soil Guide for Tillage Methods

Tillage methods are soil, crop, and climate specific. It is difficult to recommend any single tillage system for all soils and to address all soil-related constraints to crop production. Furthermore, tillage requirements vary according to the antecedent soil conditions, e.g., compaction, residue cover, etc. It is, therefore, useful to develop a soil guide to identify tillage methods in relation to soil constraints and crop requirements. The author developed a rating system to assess tillage requirements to alleviate specific soil properties. The schematic in Fig. 4 is a soil guide to tillage needs in relation to texture and soil moisture regimes. In general, no-till system is a suitable method of seed bed preparation for coarse-textured soils with good internal drainage. Heavy-textured soils with poor internal drainage do not respond favorably to a no-till system. Structurally inert soils prone to compaction and crusting also require mechanical loosening and plow-based tillage methods for water conservation and adequate root growth. In general, biostructurally active soils on undulating terrain and harsh climate should be managed with mulch tillage, no-tillage, or other reduced-tillage systems.

B. Runoff Management

Runoff management is important for soil erosion control and for efficient and sustainable use of water resources. There are at least three strategies for runoff management (Fig. 5) which include (1) decrease runoff amount, (2) reduce runoff velocity, and (3) store runoff for water recycling and future use.

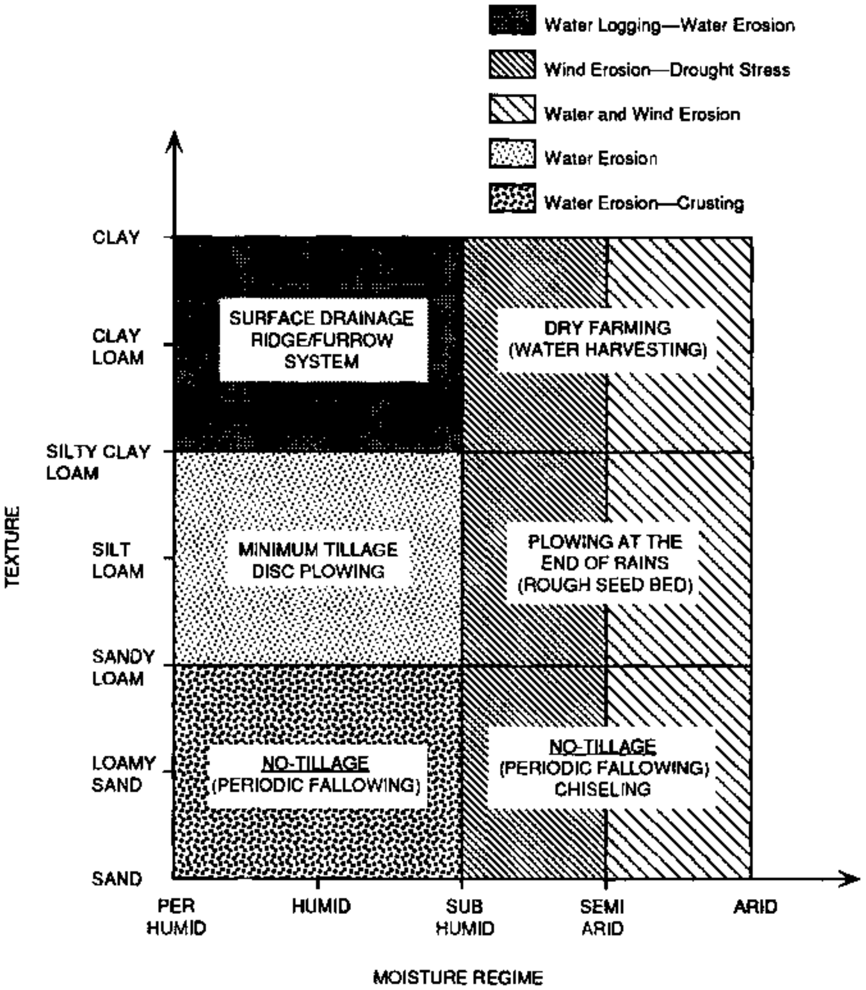

FIGURE 4 Conservation tillage systems in relation to moisture regime and soil texture. (Lal, 1985).

1. Decreasing Runoff Amount

Strategies for decreasing runoff amount involve contour farming and installing barriers on the contour.

a. Contour Farming Contouring or contour farming implies performing all farm operations on the contour rather than up and down the slope. Plowing on the contour, establishing ridge-furrow system on the contour, planting crop rows on the contour, and applying fertilizers and other chemicals on the contour increase surface detention capacity, increase time for water to infiltrate, and decrease runoff amount. Contour farming is, however, effective on gentle slopes of up to 5%. Steeper slopes require slope management techniques outlined in Fig. 5. Contour farming can be sometimes inconvenient because it possibly involves frequent turning of farm vehicles and loss of area which has to be put into buffer strips.

b. Strip Cropping Another aspect of contour farming is strip cropping or growing crops into long narrow strips established on the contour. In this system, open row crops (e.g., corn) are grown in alternate strips with close canopy crops (e.g., soybeans, alfalfa, etc.). The close canopy crop is often grown in a contour strip down slope from the open row crop. It is also important to establish buffer strips on the contour. There are various types of strip cropping. On the basis of objectives, vegetative materials used, and field design adopted, buffer strips are called contour strip cropping, buffer strip cropping, barrier strips, border strips, or field strips. In addition to reducing runoff amount, establishing strips against

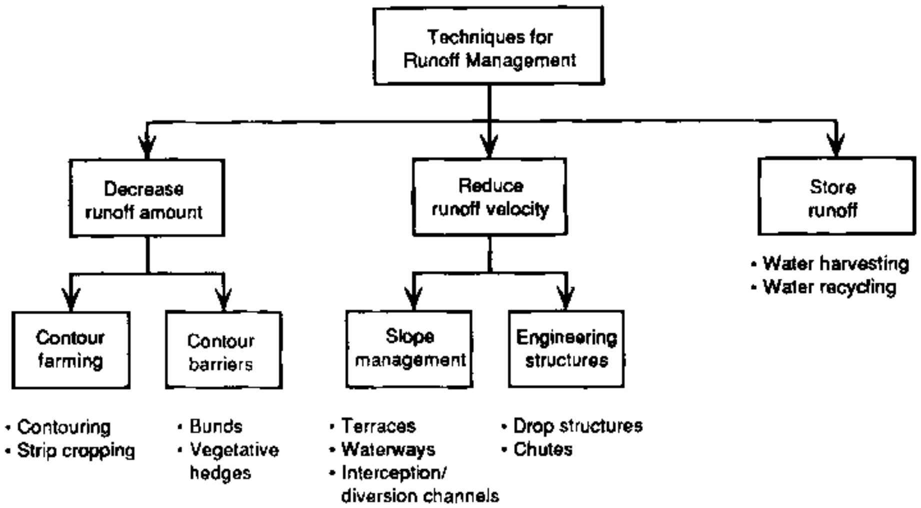

FIGURE 5 Techniques for decreasing runoff amount and velocity through engineering structures.

the prevailing wind direction also decreases wind erosion.

c. Contour Barriers Runoff amount can also be decreased by establishing contour bunds, which are embankments or earthen dikes established on the contour. These bunds are protected by establishing appropriate vegetation cover, and are particularly effective in semi-arid climates for water conservation on slowly permeable soils. Draw backs of contour bunds include extra costs, and some land area taken out of production.

d. Vegetative Hedges Rather than earthen embankments, vegetative hedges are established on the contour to create a barrier and increase time for water to soak into the soil. Vegetative hedges are mostly established from bench-type grasses. A widely adapted grass for tropical ecoregions for vegetative hedges is Vetiver (*Vetiveria zizanioides*) or khus grass. Vetiver is densely tufted bunch grass which can be easily established. In addition to grasses, vegetative hedges can also be established from woody perennials, e.g., *Leucaena leucocephala*, *Gliricidia sepium*, etc. Properly established and adequately maintained, vegetative hedges decrease runoff velocity, encourage sedimentation, and reduce runoff and soil erosion. However, closely spaced and narrow strips of grass or woody perennials are likely to be more effective in reducing runoff and soil erosion than narrow or single-row hedges.

2. Reducing Runoff Velocity

There are two general strategies for reducing runoff velocity: (a) slope management, and (b) special engineering structures.

a. Slope Management It involves breaking a long slope into short segments for decreasing overall slope gradient, and is an important and a widely practiced strategy for management of steep lands. Terracing is a practice of installing earthen dikes on the contour and preferably at right angle to the steepest slope for intercepting surface runoff originating from within the farm land. A terrace consists of two parts: an excavated channel and a bank or ridge on the down slope side. There are different types of terraces based on the size, shape, gradient, location, and protective material used for the channel vis-a-vis the ridge. Commonly used terms are graded channel terraces, stone terraces, broad-based terraces, etc. Terrace nomenclature is also based on the objective or use, e.g., orchard terraces, convertible terraces, individual basins, etc. Parameters for terrace design include shape, size, and gradient for channel; vertical/horizontal interval between terraces; and protective system to stabilize dikes and embankment. The design also includes expected runoff volume on the basis of 10-, 50-, or 100-year storm. While overdesigning is expensive, underdesigning can cause overflow and breach in terrace leading to severe gullying.

b. Waterways Installing waterways, another aspect of reducing runoff velocity, involves broad-based natural or artificial channels conveniently installed for safe disposal of surplus runoff originating from terraces and within the field. Waterways are called grass waterways, sod waterways, or meadow strips on the basis of the nature of protective material used in stabilizing them. Similar to terraces, capacity of the waterways is also designed on the basis of expected runoff from 10-, 50-, or 100-year storm.

c. Diversion Channels Diversion channels or ditches are installed to prevent run-on from surrounding hills or adjacent land. These ditches are also called storm water diversion drains. The primary objective is to prevent flood water from entering the farm. Design criteria and guidelines for construction and installation of diversion channels also based on soil type, terrain, and expected runoff.

d. Engineering Structures Permanent mechanical structures are needed for safe disposal of concentrated runoff on steep slopes. The objective is to dissipate the kinetic energy of flow through permanent structures made of concrete and other resistant materials. There are several types of engineering structures used for this purpose. Drop structures, small dams with water storage capacity, constructed in pairs at the steepest segment of the slope, are designed to stabilize steep waterways, diversion channels, or interception ditches. The longitudinal wall of the structure is constructed across the channel and anchored onto the bank on both sides. The notch or box inlet in the wall serves as a spillway. The spilling basin is below the spillway and is designed to absorb the energy. These structures are constructed from poured concrete, cement blocks, timber, corrugated metal, etc.

Chutes are specially designed spillways constructed to transmit concentrated runoff from the highest point of the waterway to the lowest. Chutes are made of poured in concrete, and the chute outlet is usually protected with brought in stones or stone rip rap.

There are also several types of check dams constructed at strategic locations to stabilize waterways and trap sediments. Check dams may be made of concrete with a notch/box spillway or they may be made of porous materials, e.g., stones held together by a wind net. Such porous structures are also called gabions which comprise prefabricated baskets of heavy-duty wire netting and are filled with stone. Gabions are flexible in dimensions, but several baskets can be placed in series or on top of one another.

3. Water Harvesting and Recycling

It involves collecting excess runoff, natural or induced, in surface reservoir for agricultural use. Water thus harvested can be stored in surface reservoirs or ponds or in soil. Appropriate water harvesting strategies depend on soil type, terrain, and rainfall characteristics. The strategy may involve microcatchment for individual trees, ridge catchment for harvesting water from a raised bed into the furrow where crops are grown, strip catchment where alternate strips are left uncropped and deliberately treated to accentuate runoff, and large catchment where large areas are set aside to harvest water and store in above-ground or below-ground reservoirs for supplementary irrigation.

V. Conclusions

Soil and water resources of the world are finite and require careful appraisal and science-based management. Mismanagement and misuse can lead to severe problems of degradation of soil and water resources, e.g., accelerated erosion, salt buildup in the root zone, soil wetness, and anaerobiosis. Limited extent of prime agricultural land, high rates of soil degradation, and rapid increase in population are responsible for decrease in global per capita land area to 0.25 ha for arable land and 0.07 ha for irrigated land.

There are several technological options for water management including drainage for improving aeration and leaching salt out of the root zone, and supplemental irrigation for alleviating drought and prolonging the growing season.

Soil conservation involves soil surface management based on conservation tillage techniques, runoff management based on slope modification and engineering structures, and water harvesting techniques.

Basic principles of these technological options are well known. Locale-specific adaptations are needed to address specific constraints to soil type, terrain, landuse, climate, and socio-economic factors.

Implementation of soil and water management and conservation techniques is essential for sustainable use of soil and water resources and for enhancement of environmental quality.

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Soil, Chemicals: Movement and Retention

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Glossary

Adsorption and ion exchange Adsorption is a process whereby solutes bind to surfaces of soil particles to form outer or inner-sphere solute–surface site complexes, whereas ion exchange is the process whereby charged solutes replace ions on soil particle surfaces

Desorption Solute release from the soil matrix to the soil solution phase when the mechanisms are not known

Dispersion A primary process of solute spreading which occurs during water flow in soils or porous media. Often referred to as mechanical or hydrodynamic dispersion, it is due to nonuniform flow distribution due to nonuniform sizes of the conducting soil pore space, fluctuation of the flow path due to tortuosity effect, and the variation in velocity from the center of a pore (maximum value) to zero at the solid surface interface

Equilibrium retention models Mathematical formulations describing the amount of solute retained from solution when solute reactions in the soil system occur instantaneously

Hysteresis A phenomenon associated with adsorption/desorption isotherms where for a given solute concentration in solution, the amount retained by the soil is lower during adsorption in comparison to desorption

Physical/chemical nonequilibrium retention models Mathematical formulations describing the amount of solute retained from solution when reactions in the soil system are time-dependent due to physical processes (pore geometry and accessibility to retention sites) or chemical processes (chemically controlled heterogeneous reactions)

Retention/release of solutes Reactions which occur between solutes present in the soil solution and the soil matrix which may include precipitation/dissolution, ion exchange, and adsorption/desorption

Sorption Solute removal (or retention) from solution by soil when the mechanisms are not known, unlike the term adsorption which describes the formation of solute–surface site complexes

The movement of chemicals and their retention in the soil profile play a significant role in their leaching losses beyond the rootzone, availability to uptake by plants, and the potential contamination of groundwater supplies. We present commonly used approaches for predicting retention behavior of chemicals in soils. First we discuss mechanisms governing the transport of dissolved chemicals in water-saturated and water-unsaturated soils and boundary conditions commonly encountered under field conditions. Major features of single retention approaches of the reversible and irreversible kinetic type are then presented. Furthermore, general purpose models of the multiple reaction type including the two-site equilibrium-kinetic, the concurrent and consecutive multireaction, and the competitive ion exchange. Physical and chemical nonequilibrium approaches such as the two-region (mobile–immobile) and second-order kinetic models are also discussed. Illustrative examples of modeling of the fate of nitrogen, potassium, and other ions interactions are given.

I. Overview

Minimizing the use of agricultural chemicals for groundwater quality and farm profitability is of major concern nationally and within the agricultural community. Health concerns for drinking water quality must be balanced with maintaining economically viable agriculture. Central to the issue of agricultural chemical management is best management practices which maximize profit with minimum potential contamination of surface and subsurface waters. Agricultural chemicals applied to soils in large amounts are fertilizers which contain major plant nutrients namely N, P, K, and S which are applied in different forms including granular, pellets, or as a liquid. In contrast, micronutrient (e.g., B, Mo, Cu, among others) are applied sparingly and only when necessary to modify diagnosed deficiencies in the soil composition. Pesticides and insecticides are commonly applied to the soils or as foliar applications on agricultural crops and ornamental for weed and pest control. Other applied chemicals include gypsum and lime as soil amendments for the primary purposes including alteration of soil acidity/alkalinity (pH) and Al toxicity. Moreover, soils are often used as a resource for land treatment of disposal of animal and municipal wastes. Occasionally, soils receive industrial and toxic or hazardous wastes which often include organic chemicals and heavy metals, among others. [*See* FERTILIZER MANAGEMENT AND TECHNOLOGY; GROUND WATER; PEST MANAGEMENT, CHEMICAL CONTROL; SOIL, ACID; SOIL POLLUTION.]

The fate of fertilizers, pesticides, and waste chemicals applied to the soil depends on physical, chemical, and biological processes in the soil. Many of these processes are not yet well understood, however. Physical processes include solute transport according to mass flow or convection and transport due to diffusion and hydrodynamic dispersion. Physical processes are influenced by water flux density, bulk density, pore geometry or tortuosity, and the occurrence of regions within the pore space which do not contribute to solute convection (i.e., mobile–immobile regions). Chemical and biological processes in the soil environment can often involve a series of complex interactions including biological transformations or degradation, oxidation and reduction, volatilization, precipitation/dissolution, complex formation, and cation or anion exchange. Knowledge of the reactions is essential for the purpose of predicting the retention reactions of solute in soils and their potential mobility to within the soil profile. The ability to predict the mobility of applied chemicals in the soil is a prerequisite in any program aimed at achieving optimum farm profitability while protecting groundwater quality. [*See* SOIL CHEMISTRY; SOIL MICROBIOLOGY.]

In this article, the principles governing the transport of solutes in soils are presented. The equation of mass conservation of solutes is given and the convection–dispersion equations for nonreactive and reactive solutes in soils are formulated. The general form of the convection–dispersion transport equation for water-unsaturated and transient water flux is derived. Major features of mechanistic models which describe the extent of adsorption/desorption or retention of solutes in soils are presented. Single reaction models of the equilibrium and kinetic types are discussed. Retention reactions of fully reversible and irreversible types are incorporated into the transport equation. Models of the multisite or multiple reaction type including the two-site equilibrium-kinetic models, the concurrent and consecutive multireaction models, and the second-order approach are presented. This is followed by multicomponent or competitive type models where ion exchange is considered the dominant retention mechanism. Incorporation of the role of specific sorption as a mechanistic approach for adsorption of ions on high-affinity sites is discussed. Moreover, selected experimental data sets are described for the purpose of model evaluation and validation. Finally, the two-region approach is described to introduce physical nonequilibrium behavior during transport in soils.

II. Transport

To describe the general equation dealing with the transport of dissolved agricultural chemicals present in the soil solution, a number of definitions must be given. For a given bulk volume within the soil, the total amount of solute χ (μg cm^{-3}) for a species *i* may be written as

$$\chi_i = \Theta C_i + \rho S_i, \tag{1}$$

where S is the amount of solute retained by the soil (μg g^{-1} soil), C is the solute concentration in solution (μg ml^{-1}), Θ is the soil moisture content (cm^3 cm^{-3}), and ρ is the soil bulk density (g cm^{-3}). The rate of change of χ for the *i*th species with time is subject to the law of mass conservation such that (omitting the subscript *i*)

$$\frac{\partial(\Theta C + \rho S)}{\partial t} = -\operatorname{div} J - Q \tag{2}$$

or

$$\frac{\partial(\Theta C + \rho S)}{\partial t} = -\left(\frac{\partial J_x}{\partial x} + \frac{\partial J_y}{\partial y} + \frac{\partial J_z}{\partial z}\right) - Q. \quad (3)$$

where t is time (hr) and J_x, J_y, and J_z represent the flux or rate of movement of solute species i in the x, y, and z directions (μg cm^{-2} hr^{-1}), respectively. The term Q represents a sink (Q positive) or source which accounts for the rate of solute removal (or addition) irreversibly from the bulk solution (μg cm^{-3} hr^{-1}). The irreversible term Q can also be considered as a root uptake term for the extraction of ions from the soil solution. For one-dimensional flow in the z-direction, the flux J_z in the soil may be given by

$$J_z = -\Theta(D_m + D_L)\frac{\partial C}{\partial z} + qC, \quad (4)$$

where D_m is the molecular diffusion coefficient (cm^2 hr^{-1}), D_L is the longitudinal dispersion coefficient (cm^2 hr^{-1}), and q is Darcy's flux (cm hr^{-1}). Therefore, the primary mechanisms for solute movement are due to diffusion plus dispersion and by mass flow or convection with water as the water moves through the soil. The molecular diffusion mechanism is due to the random thermal motion of molecules in solution and is an active process regardless of whether there is net water flow in the soil. A well-known description of the diffusion process is Fick's law of diffusion where the flux is proportional to the concentration gradient. The longitudinal dispersion term of Eq. (4) is due to the mechanical or hydrodynamic dispersion phenomenon which is due to the nonuniform flow velocity distribution during fluid flow in porous media. Nonuniform velocity distribution through the soil pores is a result of variations in pore diameters along the flow path, fluctuation of the flow path due to tortuosity effect, and the variation in velocity from the center of a pore (maximum value) to zero at the solid surface interface (Poiseuille's law). The effect of dispersion is that of solute spreading which is a tendency opposite to that of piston flow. Dispersion is effective only during fluid flow, so that for a static water condition or when water flow is near zero, molecular diffusion is the dominant process for solute transport in soils. For multidimensional flow, longitudinal dispersion coefficient (D_L) and transverse dispersion coefficients (D_T) are needed to describe the dispersion mechanism. Longitudinal dispersion refers to that in the direction of water flow and that for the transverse directions for dispersion perpendicular to the direction of flow. Based on experimental values of D_L determined by various scientists, a unique relationship exists between (D_L/D_m) and the Peclet number P ($= vd/D_m$), where d is the average diameter of the soil particles (cm) and v is referred to as the pore-water velocity and is given by (q/Θ). Based on these findings a generalized relation for D_L may be written as

$$D_L = \lambda v, \quad (5)$$

where λ is a characteristic property of the porous media known as the dispersivity (cm). Apparent dispersion D is often introduced to simplify the flux Eq. (4) such that

$$J_z = -\Theta D\frac{\partial C}{\partial z} + qC, \quad (6)$$

where D ($= D_m + D_L$) refers to the combined influence of diffusion and hydrodynamic dispersion for dissolved chemicals in porous media. Unless the water flow velocity is extremely slow, D is dominated by longitudinal dispersion D_L. Moreover, since D_m is difficult to quantify, direct methods are often used to determine the apparent dispersion coefficient D of Eq. (6). Miscible displacement results for a tracer (e.g., Br, ^3H_2O or ^{36}Cl) in soil columns are the required data set. Determination of D is obtained through either regression or trial and error by curve fitting of effluent data to analytical solution of the transport equation for nonreactive solutes. [*See* Soil–Water Relationships.]

Incorporation of flux Eq. (6) into the conservation of mass Eq. (3) yields the following generalized form for solute transport in soils in one-dimension,

$$\frac{\partial \Theta C}{\partial t} + \rho\frac{\partial S}{\partial t} = \frac{\partial}{\partial z}\left[\Theta D\frac{\partial C}{\partial z}\right] - \frac{\partial qC}{\partial z} - Q. \quad (7)$$

The above equation is commonly known as the convective–dispersive equation for solute transport which is valid for soils under transient and unsaturated soil–water flow conditions. In order to describe the fate of solutes in unsaturated soil profiles under transient flow conditions, Richards' equation for water flow (in one-dimension) must also be considered,

$$\frac{\partial \Theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z}\right] - \frac{\partial K(h)}{\partial z} - A(z,t), \quad (8)$$

where h is the soil–water pressure head (cm) and $K(h)$ is the soil hydraulic conductivity (cm hr^{-1}). The above equation is known as the h-form of the water flow equation. Knowledge of the functional relation of K versus pressure head h and the moisture characteristic relation (Θ versus h) are prerequisites for solving Richards' flow equation. In addition, Eq. (8) includes a root uptake term $A(z,t)$, for water extraction as a function of depth and time ($cm^3\ cm^{-3}\ hr^{-1}$). This term is analogous to the irreversible source/sink term Q for solutes in Eq. (7). Upon solution of Eq. (8) subject to the appropriate initial and boundary conditions, one can obtain the water content Θ and Darcy flux q for any depth (z) and time (t). Both $\Theta(z,t)$ and $q(z,t)$ are needed in order to obtain a solution for solute transport in the convection–dispersion equation.

For conditions where steady water flow is dominant, q and Θ are constants, i.e., for uniform Θ in the soil, we have the simplified form of the convection-dispersion equation as

$$\frac{\partial C}{\partial t} + \frac{\rho}{\Theta}\frac{\partial S}{\partial t} = D\frac{\partial^2 C}{\partial z^2} - v\frac{\partial C}{\partial z} - \frac{Q}{\Theta}. \qquad (9)$$

Solutions of the above convection–dispersion Eq. (7) or (9) yield the concentration distribution of the amount of solute in soil solution C and that retained by the soil matrix S with time and depth in the soil profile. In order to arrive at such a solution, the appropriate initial and boundary conditions must be specified. Several boundary conditions are identified with the problem of solute transport in porous media. First-order type boundary conditions for a solute pulse input may be described as

$$C = C_o, \qquad z = 0, \qquad t < T, \qquad (10)$$

$$C = 0, \qquad z = 0, \qquad t \geq T, \qquad (11)$$

where C_i ($\mu g\ cm^{-3}$) is the concentration of the solute species in the input pulse. The input pulse application is for a duration T which is then followed by a pulse input which is free of such a solute. Third-type boundary conditions are commonly used and account for advection plus dispersion across the interface. For a continuous input at the soil surface we have

$$vC_i = -D\frac{\partial C}{\partial z} + vC, \qquad z = 0, \qquad t > 0. \quad (12)$$

For a flux type pulse-input we have

$$vC_i = -D\frac{\partial C}{\partial z} + vC, \qquad z = 0, \qquad t < T. \quad (13)$$

The boundary conditions at some depth L in the soil profile are often expressed as

$$0 = -D\frac{\partial C}{\partial z} + vC, \qquad z = 0, \qquad t \geq T \quad (14)$$

$$\frac{\partial C}{\partial z} = 0, \qquad z = L, \qquad t \geq 0, \qquad (15)$$

which is used to deal with solute effluent from soils having finite depths. However, it is often convenient to solve the dispersion–convection equation where a semi-infinite rather than a finite length (L) of the soil is assumed. Under such circumstances, the appropriate condition for a semi-infinite medium is

$$\frac{\partial C}{\partial z} = 0, \qquad z \to \infty, \qquad t \geq 0. \qquad (16)$$

Analytical solutions to the convection–dispersion equation subject to the appropriate boundary and initial conditions are available for a limited number of situations whereas the majority of the solute transport problems must be solved using numerical approximation methods. In general, whenever the form of the retention reaction is linear, a closed-form solution is obtainable. A number of closed-form solutions are available in the literature. However, most retention mechanisms are nonlinear and time-dependent in nature and analytical solutions are not available. As a result a number of numerical models using finite-difference or finite element approximations have been utilized to solve nonlinear retention problems of multireaction and multicomponent solute transport for one- and two-dimensional geometries.

III. Single Retention Models

The reversible term ($\partial S/\partial t$) and the irreversible tern Q of Eqs. (7) and (9) must be identified in order tc predict the fate of reactive solutes in the soil. Th reversible term is often used to describe the rate o sorption or exchange reactions with the solid matrix Sorption or exchange has been described by eithe instantaneous equilibrium or a kinetic reaction wher C and S vary with time. Linear, Freundlich, and one and two-site Langmuir equations are perhaps the mos commonly used to describe equilibrium reactions. Io exchange is often considered instantaneous in natur and governs the retention of cations such as Ca, Mg, and Na in soils. In contrast, retention for several solutes has been observed to be strongly time-dependet (e.g., phosphorus, several heavy metals, and orga ics). Selected examples of kinetic retention for P ar given in Fig. 1. The influence of kinetic reactions on the shape of sorption isotherms of P for an Oldsmar fine sand (from south Florida) is clearly illustrated in Fig. 1. The amount of P removed from solution increased with P concentration and time. Several approaches have been proposed to describe kinetic retention behavior such as that shown in Fig. 1. First-order kinetic is perhaps the earliest single form of reaction used to describe sorption versus time for several solutes in soils.

$$\rho\frac{\partial S}{\partial t} = k_f \Theta C - k_b \rho S. \tag{17}$$

The reaction is reversible with k_f and k_b representing the forward and backward rate coefficients (hr^{-1}). Integration of Eq. (17) subject to initial conditions of $C = C_o$ and $S = 0$ at $t = 0$, yields a system of linear sorption isotherms. That is, following any reaction time t, a linear relation between S and C is obtained. However, linear isotherms are not often encountered except for selected cations, heavy metals, and pesticides at low concentrations. In contrast, nonlinear retention behavior is commonly observed for several solutes as depicted by the nonlinear isotherms for P shown in Fig. 1. As a result, the single reaction given by Eq. (17) has been extended to include the nonlinear kinetic form,

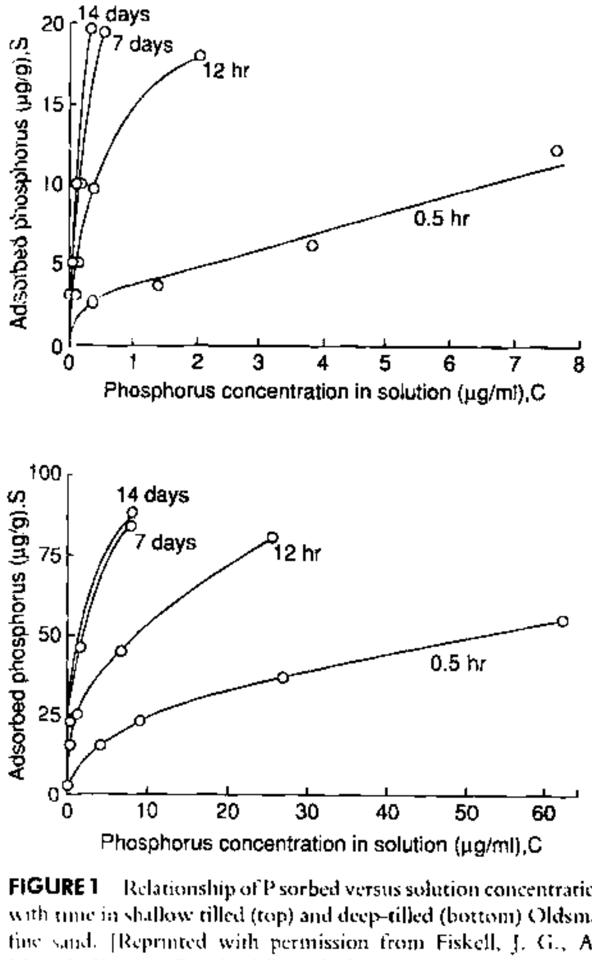

FIGURE 1 Relationship of P sorbed versus solution concentration with time in shallow tilled (top) and deep-tilled (bottom) Oldsmar fine sand. [Reprinted with permission from Fiskell, J. G., A., Mansell, R. S., Selim, H. M., and Martin, G. G. (1979). Kinetic behavior of phosphate sorption by acid sandy soil. *J. Environ. Qual.* **8,** 579–584.]

$$\rho\frac{\partial S}{\partial t} = k_f \Theta C^m - k_b \rho S, \tag{18}$$

where m is a dimensionless parameter commonly less than unity and represents the order of the nonlinear reaction. For both single kinetic forms (Eqs. 17 and 18), the magnitude of the rate coefficients dictates the extent of the kinetic behavior of the reaction. For small values of k_f and k_b, the rate of retention is slow and strong kinetic dependence is anticipated. In contrast, for large values of k_f and k_b, the retention reaction is rapid and should approach quasi-equilibrium in a relatively short time. In fact, at large times ($t \rightarrow \infty$) equilibrium is attained and the rate of retention ($\partial S/\partial t$) approaches zero and Eq. (18) yields,

$$S = K_d C^m,$$

where

$$K_d = \left(\frac{\Theta}{\rho}\right)\frac{k_f}{k_b}, \tag{19}$$

which is analogous to the Freundlich equilibrium equation where K_d is the distribution coefficient ($\text{cm}^3\,\text{g}^{-1}$). For Freundlich or linear isotherms ($m = 1$), one may regard K_d as the ratio of the forward rate coefficient for sorption to that for desorption or release (backward reaction). An alternative to the first- or nth order models is that of the second-order kinetic approach. This approach is commonly referred to as the Langmuir kinetic and has been used for P retention and sorption of heavy metals by high-affinity or specific sites. According to second-order formulation, the rate of retention is a function of solution concentration and the amount of available retention sites on matrix surfaces such that

$$\rho\frac{\partial S}{\partial t} = k_f \Theta \phi C - k_b \rho S \tag{20}$$

or

$$\rho\frac{\partial S}{\partial t} = k_f \Theta (S_T - S) C - k_b \rho S, \tag{21}$$

where ϕ is the amount of available or vacant sites and S_T is the total amount of sorption sites (μg g^{-1}). Available or vacant specific sites are not strictly vacant. They are assumed occupied by hydrogen, hydroxyl, or other specifically sorbed species. At $t \rightarrow \infty$, when the reaction achieves local equilibrium, the second-order Eq. (20) obeys the widely recognized Langmuir sorption isotherm equation

$$\frac{S}{S_T} = \frac{\omega C}{1 + \omega C}, \tag{22}$$

where ω ($= \Theta k_f/\rho k_b$) is the (equilibrium) Langmuir coefficient. Sorption/desorption studies showed that highly specific sorption mechanisms are responsible for solute retention at low concentrations. The general view is that metal ions have a high affinity for sorption sites of oxide minerals surfaces in soils.

Adsorption–desorption hysteretic behavior has been observed by several scientists. Examples of hysteretic behavior for atrazine adsorption–desorption isotherms for a Sharkey clay soil from Louisiana are given in Fig. 2. Atrazine desorption shows significant hysteresis or nonsingularity behavior which becomes apparent with increasing incubation time. The adsorption and desorption isotherms are nearly identical for the case where no incubation time was allowed and desorption for six consecutive steps were followed. If adsorption and desorption isotherms are identical and follow the same path, i.e., nonhysteretic behavior, the retention is regarded as fully reversible where local equilibrium is dominant. Based on the hysteresis behavior for several initial concentrations (not shown), desorption results suggest that part of the adsorbed atrazine is not easily desorbed or becomes nondesorbable by forming strong complexes or due to degradation to more strongly adsorbed hydroxyatrazine or other metabolites. It has been shown theoretically that hysteresis results from failure to achieve equilibrium during adsorption or desorption. If adsorption and desorption are carried out for times sufficient for equilibrium to be attained, or the kinetic rate coefficients are sufficiently large, such hysteretic behavior is minimized.

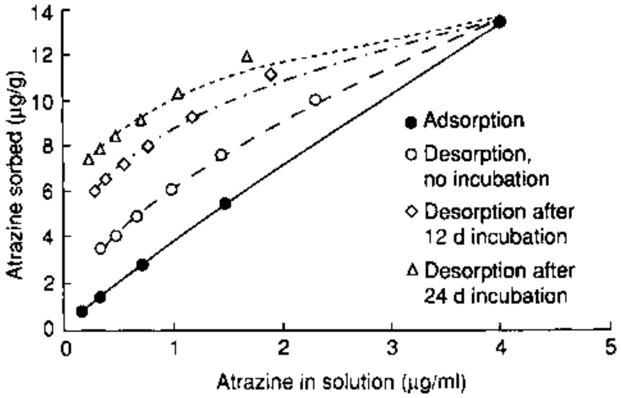

FIGURE 2 Atrazine adsorption–desorption hysteresis isotherms for a Sharkey clays soil.

IV. Transport and Ion Exchange

Modeling cation retention and transport in the soil profile requires knowledge of several chemical and physical properties of the soil matrix, including the cation exchange capacity and the distribution of exchangeable cations between solution and sorbed phases. Only recently, competitive ion exchange of cations in the soil solution during transport in soils was considered. The simplest model is that for a binary system based on the convective–dispersive equation with cation retention during steady water flow in soils. Reversible ion exchange is considered to govern the retention of cations present in the soil. In addition, the ion-exchange reactions are assumed to be rapid or instantaneous which implies that local equilibrium conditions are dominant. A set of recursion equations is needed to describe multispecies, heterovalent cation exchange, however. Examples of predictions of breakthrough curves (BTCs) using ion-exchange models compared to experimental data for pulses of Mg plus Na leached by Ca in a Sharkey clay soil column is shown in Fig. 3. Breakthrough of Na was early and well described by the model. The retardation of Ca and Mg peaks were accurately described; however, peak heights were not well estimated. Nev-

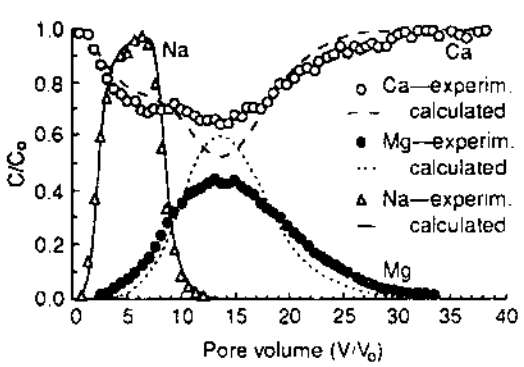

FIGURE 3 Breakthrough results, pore volume (V/V_0) and relative concentration (C/C_0) for a ternary (Na–Ca–Mg) system in a Sharkey soil. Solid curves are predictions using equilibrium ion exchange transport model. [Reprinted with permission from Gaston, L. A., and Selim, H. M. (1990). Transport of exchangeable cations in an aggregated clay soil. *Soil Sci. Soc. Am. J.* **54**, 31–38.]

ertheless these predictions are surprising achievements for simple transport models based on ion exchange.

Predicting cation transport in soils as shown in Fig. 3 requires knowledge of several chemical and physical properties of the exchange medium including, at a minimum, the cation exchange capacity (CEC), exchange selectivity coefficients, bulk density, and the dispersion coefficient. The CEC and the physical properties are fairly readily determined. Estimation of cation exchange selectivities, however, typically requires development of exchange isotherms. The experimental methods are laborious. If exchange selectivities for reference materials could be used to obtain fairly accurate predictions of cation movement in field soils then it might be feasible to broaden the data base of land management decisions for agricultural production or waste disposal to include such predictions. The applicability of selectivity parameters of a common type of soil mineral for prediction of cation mobilities in soils having mineralogies dominated by a similar mineral was recently investigated. To achieve this goal, the determination of a data base for pure clays such as that shown in Fig. 4 was essential. Transport model predictions based on selectivity coefficients on pure montmorillonite, as obtained from Fig. 4, adequately described cation leaching in columns of bulk samples of a predominantly montmorillonitic Sharkey soil. Experimental and predicted effluent results of Na and Mg applied to a Ca-saturated Sharkey soil are shown in Fig. 5. In addition, comparison of predictions of binary (Ca–Mg) or ternary (Ca–Mg–Na) transport using selectivity coefficients on pure montmorillonite to transport in columns of Olivier series (fine silty, mixed, thermic, Aquic Fragiudalf) and Yolo series (fine silty, mixed, nonacid, thermic, Typic Xerorthent) revealed generally good agreement. These results for one common clay mineral are encouraging. However, the applicability of exchange data for pure clays to description of cation transport in soils is not possible until the transport or exchange behavior in several such soils is examined.

Several studies showed that ion exchange is a kinetic process in which local equilibrium was not reached instantaneously. In fact, an extensive list of cations (and anions) exhibited kinetic ion exchange behavior in soils (e.g., aluminum, ammonium, potassium, and several heavy metal cations). The extent of the kinetics of potassium retention on kaolinite, montmorillonite, and vermiculite is illustrated in Fig. 6. A single first-

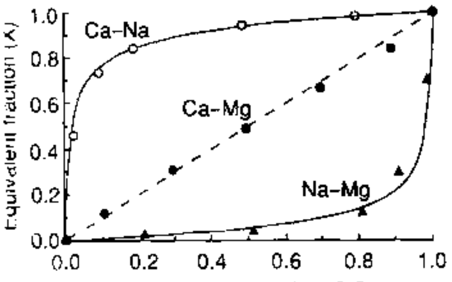

FIGURE 4 Exchange isotherm for bentonite clay in 0.05 M ClO$_4$ background solution. Solid curves are predictions based on average selectivities. [Reprinted with permission from Gaston, L. A., and Selim, H. M. (1990). Predictions of cation mobility in montmorillonitic media based on exchanged selectivities of montmorillonite. *Soil Sci. Soc. Am. J.* **54**, 1525–1530.]

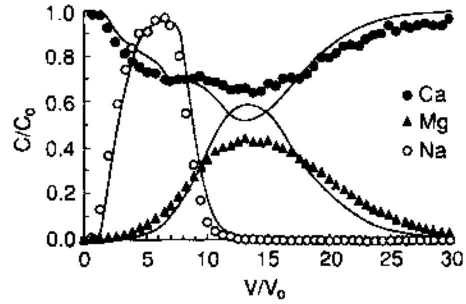

FIGURE 5 Breakthrough results, pore volume (V/V_0) and relative concentration (C/C_0) for a ternary (Na–Ca–Mg) system in a Sharkey soil. Predictions are based on exchange isotherm data for bentonite clay. [Reprinted with permission from Gaston, L. A., and Selim, H. M. (1990). Predictions of cation mobility in montmorillonitic media based on exchange selectivities of montmorillonite. *Soil Sci. Soc. Am. J.* **54**, 1525–1530.]

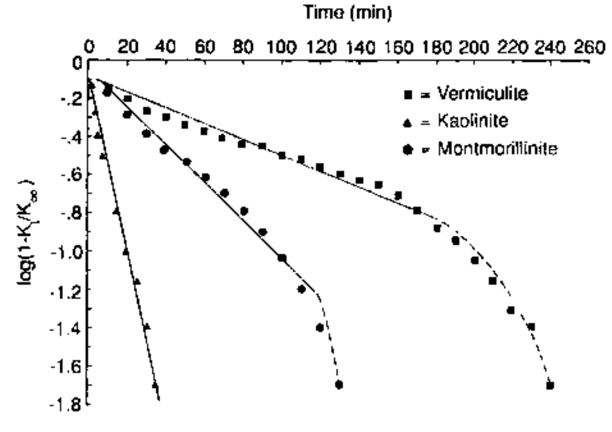

FIGURE 6 First-order plots of potassium adsorption on clay minerals where K_t is quantity adsorbed at time t and K_∞ is quantity adsorbed at equilibrium. [Reprinted with permission from Jardine, P. M., and Sparks, D. L. (1984). Potassium-calcium exchange in a multireactive soil system. I. Kinetics. *Soil Sci. Soc. Am. J.* **48**, 39–45.]

order decay type reaction described the data adequately for kaolinite and montmorillonite whereas two first-order reactions were necessary to describe potassium retention on vermiculite. Deviations from first-order kinetics for longer reaction time is likely due to the fact that potassium retention is not an irreversible but rather a reversible mechanism. At large times, the contribution of the reverse or backward retention process becomes significant and thus should not be ignored. Kinetic ion-exchange behavior in soils is probably due to mass transfer (or diffusion) and chemical kinetic processes. For chemical sorption to occur, ions must be transported to active (fixed) sites of the soil particles. The film of water adhering to and surrounding the particles and water within the interlayer spaces of the particles are both zones of low concentrations due to depletion by adsorption of ions onto the exchange sites. The decrease in concentration in these two interface zones may be compensated by diffusion of ions from the bulk solution. Therefore, a kinetic ion-exchange model formulation was recently developed analogous to mass transfer or diffusion between the solid and solution phase such that,

$$\frac{\partial S}{\partial t} = \gamma \, (S^{\star} - S), \qquad (23)$$

where S is the amount sorbed on exchange surfaces, $S^{\star}$ is the equilibrium sorbed amount (at time t), and γ is an apparent rate coefficient (h^{-1}). Here, the sorbed amount was calculated using the respective sorption equilibrium condition based on laws of mass action governing ion exchange processes. Expressions similar to the above have been used to describe chemical kinetics as well as mass transfer between mobile and immobile water.

V. Multiple Reaction Models

Several studies showed that sorption–desorption of dissolved chemicals on several soils was not adequately described by use of a single reaction of the equilibrium or kinetic types. Failure of single reactions is not surprising since they only describe the behavior of one species with no consideration to the simultaneous reactions of others in the soil system. Multisite or multireaction models deal with the multiple interactions of one species in the soil environment. Such models are empirical in nature and are based on the assumption that retention sites are not homogeneous in nature, rather the sites are heterogeneous and thus have different affinities to individual solute species. One of the earliest multireaction models is the two-site model which was developed in order to describe observed batch results which showed rapid initial retention followed by slower type reactions. It was also developed to describe observed excessive tailing of BTCs from pulse inputs in miscible displacement experiments. The two-site model is based on several simplifying assumptions. First it is assumed that a fraction of the total sites (referred to as type I sites) reacts rapidly with the solute in soil solution. In contrast, type II sites are highly kinetic in nature and react slowly with the soil solution. The retention reactions for both types of sites were based on the nonlinear (or *n*th order) reversible kinetic approach discussed earlier.

The two-site approach was also adapted for the case when type I sites were assumed to be in equilibrium with the soil solution whereas type II sites were considered of the kinetic type. The two-site model provided improved pesticide predictions of the excessive tailing of the desorption or leaching side and the sharp rise of the sorption side of the BTCs in comparison to predictions with single reaction equilibrium or kinetic models. The model proved successful in describing the retention and transport of several dissolved chemicals including aluminum, 2,4-D, atrazine, phosphorus, potassium, cadmium, chromium, and methyl bromide. However, there are several inherent disadvantages of the two-site model. The reaction mechanisms are restricted to those which are fully reversible. Moreover, the model does not account for possible consecutive type solute interactions in the soil system.

Due to the limitations of the single reaction approach, several multireaction models which account for multiple reactions (reversible and irreversible) of solutes during transport in soils have been proposed. An example is a phosphorus multireaction and transport model which includes different sorption sites for P reactions in soils shown in Fig. 7. It is assumed that applied P in a dissolved form is subject to six reversible-kinetic reactions that are assumed to control the transfer of applied P between solution, adsorbed, immobilized, and precipitated phases within the soil. Sinks are shown for irreversible removal of P from the soil solution by plant uptake and leaching. Model formulation is based on the observed slow reaction of P in soils which may represent chemisorption or diffusion into the micropore space of soil aggregates. Moreover, kinetic P behavior may be physically controlled by the geometry of the soil pore space as well as the accessibility of retention sites to P in

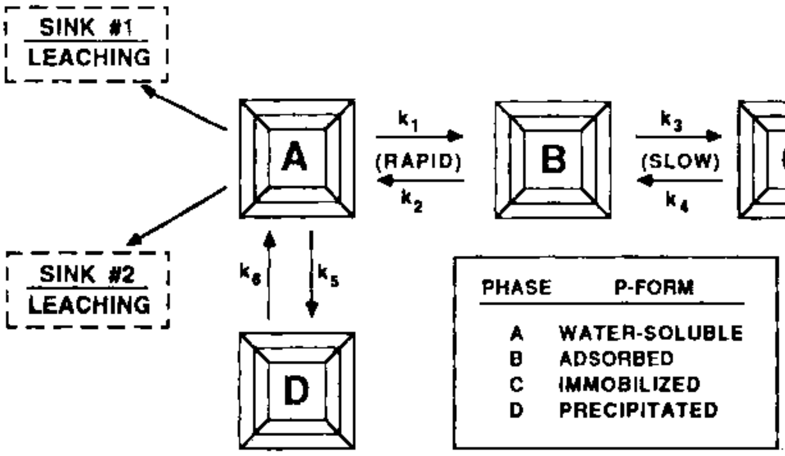

FIGURE 7 A schematic representation of six reversible-kinetic reactions that are assumed to control the transfer of applied phosphate (P) between solution, adsorbed, immobilized (chemisorbed), and precipitated phases within the soil. Sinks are shown for irreversible removal of P from the soil solution by plant uptake and leaching. [Reprinted with permission from Mansell, R. S., Selim, H. M., and Fiskell, J. G. A. (1977). Simulated transformations and transport of phosphorus in soils. *Soil Sci.* **124,** 102–109.]

the bulk solution. The presence of inaccessible sites is proposed as a controlling mechanism of the slow decline of P in the soil solution with time. Such a slow process may be caused by solid diffusion of surface phosphate within soil particles. It may also be due to differences in rates of reactions which occur between P and different reaction sites of the soil matrix.

A schematic representation of the reactions of K in soils is illustrated in Fig. 8. This empirical multireaction approach considers kinetic reactions to govern transformation between solution, exchangeable, nonexchangeable (secondary minerals), and primary mineral phases of K in soils. The first two compartments account for K uptake by plant roots and transport of K due to mass flow and dispersion. The subsequent compartments deal with reversible reactions of adsorption/desorption between the solution and exchangeable phases. The transformations of exchangeable, nonexchangeable (secondary minerals), and primary mineral phases are considered time-dependent and dictated by extremely slow rates of reactions.

One should recognize that a multireaction model cannot account for all possible interactions occurring with the soil system. For example, characterization of chemical, biological, and physical interactions of nitrogen within the soil environment is a prerequisite in the formulation of a multireaction nitrogen model. One major point is how strongly such factors affect nitrogen behavior and distribution within soil systems. Among these factors are: the effect of soil texture and structure on oxygen diffusion; distribution of plant residues (vertically and horizontally) which affects infiltration rates, leaching, and biological transformations including plant uptake, mineralization, and denitrification; as well as cultural practices, such as tillage and fertilizer distribution which affect nitrogen distribution vertically and horizontally. Since nitrate is a highly mobile nitrogen form that can leach through the soil profile and eventually into groundwater, the goal of any nitrogen management plan must include minimizing nitrate leaching from agricultural activities into groundwater. Nevertheless, description of N dynamics in the soil is often simplified. To illustrate this, one needs to examine the N dynamics in soils as described in the simplified approach shown in Fig. 9. The model accounts for nitrification, denitrification, immobilization, mineralization, and ion exchange of ammonium as a reversible first-order kinetic process. To utilize such a model, despite its simplicity, requires several independent parameters (rate coefficients) many of which are not easily available. As a result, simplified versions (or submodels) of the model shown in Fig. 9 are commonly utilized for management decisions. [*See* NITROGEN CYCLING.]

VI. Two-Region Models

A number of experimental studies demonstrated early breakthrough results and tailing with nonsymmetrical concentration distributions of BTCs. Discrepancies from symmetrical or ideal behavior for several solutes led to the concept of solute transfer between mobile

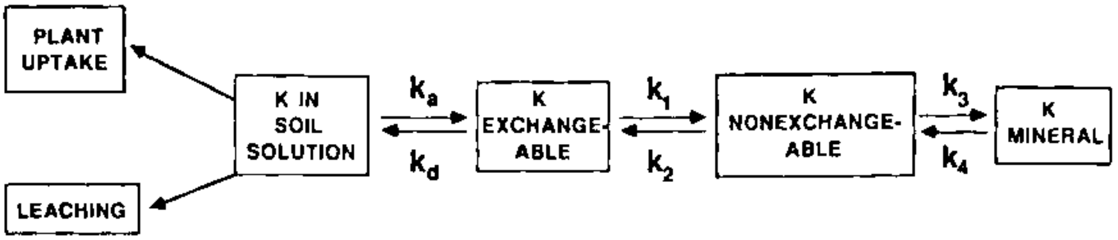

FIGURE 8 A schematic representation of the reactions of potassium (K) in solution, exchangeable, nonexchangeable (secondary minerals), and primary mineral phases in soil. [Reprinted with permission from Selim, H. M., Mansell, R. S., and Zelazny, L. W. (1976). Modeling reactions and transport of potassium in soils. *Soil Sci.* **122**, 77–84.]

and immobile waters. It was postulated that tailing under unsaturated conditions was perhaps due to the fact that larger pores are eliminated for transport and the proportion of the water that does not readily move within the soil increased. This fraction of water was referred to as stagnant or immobile water. A decrease in water content increases the fraction of air-filled macropores resulting in the creation of additional dead end pores which depend on diffusion processes to attain equilibrium with a displacing solution. However, the conceptual approach of mobile–immobile or two-region behavior is perhaps more intuitively applicable for well-structured or aggregated soils under either saturated or unsaturated flow. Here one can assume that within soil aggregates, where micropores are dominant, diffusion is the primary process. In contrast, convection and dispersion are the dominant processes in the macro (or intra-aggregate) pore space which occur between large aggregates or structural units.

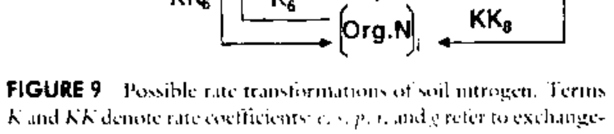

FIGURE 9 Possible rate transformations of soil nitrogen. Terms *K* and *KK* denote rate coefficients; *e*, *s*, *p*, *i*, and *g* refer to exchangeable, solution, plant, immobilized, and gaseous phases, respectively. [Reprinted with permission from Mehran, M., and Tanji, K. K. (1974). Computer modeling of nitrogen transformations in soils. *J. Environ. Qual.* **3**, 391–395.]

The equations describing the movement for a nonreactive solute through a porous media having mobile and immobile water fractions are

$$\Theta_m \frac{\partial C_m}{\partial t} + \Theta_{im} \frac{\partial C_{im}}{\partial t} = \Theta_m D_m \frac{\partial^2 C_m}{\partial z^2} - v_m \Theta_m \frac{\partial C_m}{\partial z} \tag{24}$$

and

$$\Theta_{im} \frac{\partial C_{im}}{\partial t} = \alpha (C_m - C_{im}), \tag{25}$$

where D_m is the hydrodynamic dispersion coefficient in the mobile water region, Θ_m and Θ_{im} are mobile and immobile water fractions, respectively (cm^3 cm^{-3}), C_m and C_{im} are the concentrations in the mobile and immobile water (μg cm^{-3}), and v_m is the average pore-water velocity in the mobile region. We also assume that the immobile water (Θ_{im}) is located inside aggregate pores (inter-aggregate) where the solute transfer occurs by diffusion only. In Eq. (24), α is a mass transfer coefficient (hr^{-1}) which governs the transfer of solutes between the mobile- and immobile-water phases in an analogous manner to a diffusion process. Incorporation of reversible and irreversible retention for reactive solutes in Eqs. (24) and (25) yields

$$\Theta_m \frac{\partial C^m}{\partial t} + \rho f \frac{\partial S_m}{\partial t} + \Theta_{im} \frac{\partial C_{im}}{\partial t} + \rho (1 - f) \frac{\partial S_{im}}{\partial t} = \Theta_m D \frac{\partial^2 C_m}{\partial z^2} - v_m \theta_m \frac{\partial C}{\partial z} - Q_m \tag{26}$$

and

$$\Theta_{im} \frac{\partial C_{im}}{\partial t} + \rho (1 - f) \frac{\partial S_{im}}{\partial t}) = \alpha (C_m - C_{im}) - Q_{im}. \tag{27}$$

Here the soil matrix is divided into two regions (or sites) where a fraction *f* is a dynamic or easily accessible region and the remaining fraction is a stagnant or less accessible region (see Fig. 10). The dynamic region is located close to the mobile phase whereas the stagnant region is in contact with the immobile phase. Moreover, S_m and S_{im} are the amounts of solutes sorbed in the dynamic and stagnant regions (μg g^{-1} soil), respectively. Also Q_m and Q_{im} are sink (or source) terms associated with the mobile and immobile water regions, respectively. The two-region approach was successful in describing the fate of several pesticides in soils when linear and Freundlich reversible reactions were considered. However, it is often necessary to include a kinetic rather than an equilibrium reaction to account for the degradation of pesticides in soils. The two-region approach was successfully used to describe heavy metal transport in soils when adsorption was considered as a Langmuir kinetic along with a first-order irreversible reaction as the sink term. This approach received only limited success when extended to describe the transport and ion-exchange of ions in soils for binary (Ca–Mg) and ternary (Ca–Mg–Na) systems

The two-region (mobile–immobile) is often regarded as a mechanistic approach where physical nonequilibrium is the controlling mechanism. In contrast, in the two-site (equilibrium/kinetic) approach is utilized when chemically controlled, heterogeneous reactions are the governing mechanisms. However, one can show that the two models are analogous mathematically. Therefore, analysis of data sets of effluent results from miscible displacement experiments alone could not be used to differentiate between physical and chemical processes that caused an apparent nonequilibrium situation in a soil. The similarity of the two transport models also means that the two formulations can be used in macroscopic and semi-empirical manner without having to delineate the exact physical and chemical processes on the microscopic level.

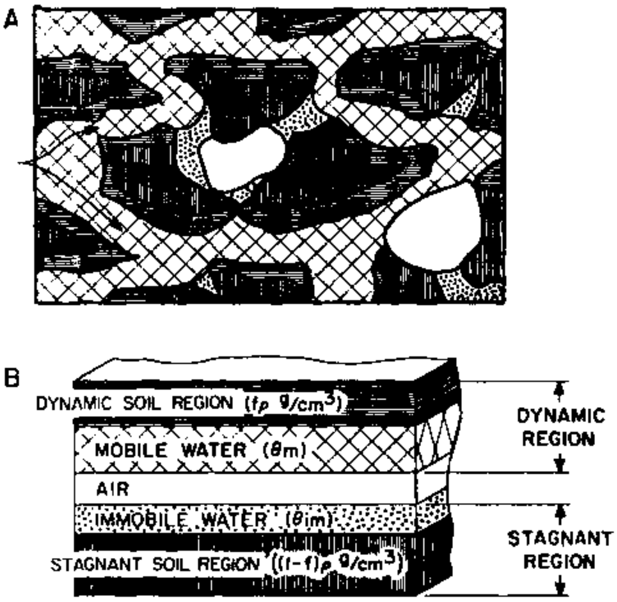

FIGURE 10 A schematic diagram of unsaturated aggregated porous medium. (A) Actual model. (B) Simplified model. The shading in A and B represent the same region. [Reprinted with permission from van Genuchten, M. Th., and Wierenga, P. J. (1976). Mass transfer studies sorbing porous media I. Analytical solutions. *Soil Sci. Soc. Am. J.* **40,** 473–480.]

Although the two-region model concept has been shown to successfully describe the appearance of lack of equilibrium behavior and tailing for a wide range of conditions, this approach has several drawbacks. First, the value of α is difficult to determine for soils because of the irregular geometric distribution of immobile water pockets. In addition, the fraction of mobile and immobile water within the system can only be estimated. Thus, two parameters are needed (for nonreacting solute) and they can only be found by curve fitting of the flow equations to effluent data. Another drawback of the mobile–immobile approach is the inability to identify unique retention reactions associated with the dynamic and stagnant soil regions separately. Due to this difficulty, a general assumption implicitly made is that similar processes and associated parameters occur within both regions. Thus, a common set of model parameters are utilized for both regions. Such an assumption has been made for equilibrium (linear, nonlinear, and ion exchange) as well as kinetic reversible and irreversible reactions. Therefore, this model disregards the heterogeneous nature of various types of sites on matrix surfaces. This is not surprising, since soils are not homogeneous systems but are complex mixtures of clay minerals, several oxides/hydroxides, and organic matter with varying surface properties. [*See* SOIL GENESIS, MORPHOLOGY, AND CLASSIFICATION.]

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Soil Chemistry

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Glossary

Adsorption Net accumulation of matter at the interface between a solid phase and an aqueous solution phase

Chemical kinetics Study of chemical reaction rates and molecular processes where transport is not limiting

Clay mineral Any crystalline inorganic substance of clay size, i.e., $<2\ \mu m$ equivalent spherical diameter

Kinetics General term referring to time-dependent phenomena

Soil chemistry Branch of soil science that deals with the chemical composition, chemical properties, and chemical reactions of soils

Transport phenomena Includes displacement of solutes and sorbates in the liquid phase, in the solid phase (soil), and at the solid/liquid interfaces

Soil chemistry is the branch of soil science that deals with the chemical composition, chemical properties, and chemical reactions of soils. Soils are heterogeneous mixtures of both inorganic and organic solids, air, water, and microorganisms. Soil chemistry is concerned with reactions involving these phases. For example, air and water weather the solids and reactions of the solids with the soil solution affect water quality. Soil chemistry has both an inorganic and organic branch; however, there is overlap between the branches. It is closely allied to various aspects of surface chemistry, geochemistry, and environmental chemistry.

I. Historical Perspective

Soil chemistry, as a subdiscipline of soil science, originated in the early 1850s in the celebrated research of J. Thomas Way, a consulting chemist to the Royal Agricultural Society in England. Way, who is considered the father of soil chemistry, carried out a remarkable group of experiments on the ability of soils to exchange ions. He found that soils could adsorb both cations and anions that could be exchanged with other ions. He noted that ion exchange was rapid, that clay was most important in the adsorption of cations, and that heating or acid treatment decreased the ability of soils to adsorb ions. The vast majority of Way's findings were correct, and he laid the groundwork for many seminal studies on ion exchange and ion sorption that were later conducted by soil chemists.

The progenitor of soil chemistry in the United States was Edmund Ruffin, a philosopher, rebel, politician, and farmer from Virginia. Ruffin fired the first Confederate cannon at Fort Sumter. He committed suicide after Appomattox because he did not wish to live under the "perfidious Yankee race." Ruffin was attempting to farm near Petersburg, Virginia, on soil that was rather unproductive. He astutely applied oyster shells to his land for the proper reason—to correct or ameliorate soil acidity. He also described zinc deficiencies quite well in his journals.

Much of the research in soil chemistry between 1850 and 1900 was an extension of Way's work. During the early decades of the 20th century classic ion exchange studies by Gedroiz in Russia, Hissink in

Holland, and Kelley and Vanselow in California extended the pioneering investigations and conclusions of Way. Numerous ion exchange equations were developed to explain and predict binary reactions on clay minerals and soils. These were named after the scientists that developed them and included the Kerr, Vanselow, Gapon, Schofield, Krishnamoorthy and Overstreet, Donnan, and Gaines and Thomas equations. These equations enable one to determine ion selectivity coefficients to predict preferences of ions on soils. Some of these selectivity coefficients were also equated to an exchange equilibrium constant. However, it would be 1951 before a rigorous thermodynamic treatment of ion exchange by Argersinger and co-workers would provide an approach for the calculation of exchange equilibrium constants (K_{eq}) and adsorbed phase activity coefficients.

In the 1930s a major discovery was made by Hendricks and co-workers and Kelley and co-workers who found that clay minerals in soils were crystalline. Shortly thereafter, X-ray studies were conducted to identify clay minerals and to determine their structures. Immediately, studies were carried out to investigate the retention of inorganic and organic species in clays, oxides, and soils and the mechanisms of retention were proposed. Particularly noteworthy were early studies conducted by Schofield and Mehlich who validated some of Sante Mattson's earlier theories on sorption phenomena. These studies were the forerunners of one of the hallmarks of soil chemistry research—surface chemistry of soils.

One of the most interesting and important bodies of research in soil chemistry has been that of the chemistry of soil acidity. As Hans Jenny so eloquently wrote, investigations on soil acidity were like a merry-go-round. Fierce arguments ensued about whether acidity was primarily attributed to hydrogen or aluminum and were the basis for many studies during this century. The work of Samuel Johnson, F. P. Vietch, C. G. Hopkins, Emil Truog, Jenny, R. Bradfield, C. E. Marshall, V. A. Chernov, H. Paver, P. F. Low, Michael Peech, N. T. Coleman, M. E. Harward, and C. I. Rich were particularly elegant and important. It was Coleman and Rich who concluded that aluminum, trivalent, monomeric, and polymeric hydroxy, was the primary culprit in soil acidity. [*See* SOIL, ACID.]

Another important historical debate in soil chemistry involved the heated, and often caustic, arguments over the cause of the suspension effect, the observation that soil pH is usually lower in the paste than in the supernatant of a soil and water mixture. Marshall in Missouri and M. Peech at Cornell attributed the suspension effect to a Donnan membrane phenomenon, while Jenny and his co-workers, particularly Coleman, ascribed the suspension effect to a liquid junction potential. Jenny and co-workers reasoned that when the salt bridge electrode was placed in contact with the soil, the mobilities of potassium and chloride ions were no longer similar, as they would be in aqueous solution. This alteration in mobilities was ascribed to the attraction of the potassium ions to the charged soil surface. Thus, a junction potential was created resulting in a lower pH reading. This debate, while never definitively resolved, involved some of the most outstanding soil chemists of modern times.

Studies on soil acidity, ion exchange, the suspension effect, and sorption of ions by soils and soil components such as clay minerals and hydrous oxides were major research themes of soil chemists for many decades. Without question, for over 100 years, the major emphasis in soil chemistry was the effects of soil chemical reactions on plant growth and plant nutrition.

Beginning in the 1970s, and certainly in the 1990s, the emphasis in soil chemistry and the research endeavors of soil chemists have shifted heavily to studies on environmental quality. In fact, many soil chemists are referring to themselves as environmental soil chemists and there are increasing interactions between soil chemists and environmental engineers, chemical engineers, agricultural engineers, geochemists, chemists, and material scientists. Most likely, the major emphasis of soil chemistry over the next few decades, and perhaps beyond, will be on environmental soil chemistry.

Throughout the world, concerns have been expressed about a number of soil and water contaminants. These include nitrates and phosphates, heavy metals such as arsenic, cadmium, chromium, copper, lead, mercury, and nickel, radionuclides, pesticides, industrial chemicals, and pollutants in municipal sludges and animal wastes. At present, studies on the following environmental soil chemistry topics are prevalent throughout the world: rates and mechanisms of heavy metal, radionuclide, pesticide, and industrial pollutant interactions with soils and soil components; the environmental chemistry of aluminum in soils, particularly acid rain effects on soil chemical processes; oxidation–reduction phenomena involving soils and soil components and inorganic and organic contaminants; and chemical interactions of sludges, manures, and industrial byproducts and coproducts with soils. [*See* SOIL POLLUTION.]

To make major advances in the above areas, it is no longer enough to conduct only macroscopic, equilibrium-based investigations. We must increasingly study the kinetics of soil chemical phenomena and employ modern, surface spectroscopic and microscopic techniques to elucidate mechanisms of pollutant interactions in soils. Such studies will help us to speciate contaminants in soils, to understand interactions of metals and organics with soils and assist in developing strategies for mitigating pollutant mobility into surface and groundwaters, and to develop effective and economically feasible approaches for remediating polluted soils.

Before discussing some of the themes in modern soil chemistry, it would be instructive to discuss characteristics of soil minerals. The chemical properties and the types of chemical reactions that occur in soils are dramatically affected by the types of inorganic and organic components found in a given soil.

II. Soil Minerals

A. Inorganic Minerals

Inorganic minerals in soils can be divided into primary and secondary minerals. Primary minerals are less weathered than secondary minerals and are formed from parent material. The secondary minerals form as weathering products of primary minerals. [*See* SOIL GENESIS, MORPHOLOGY, AND CLASSIFICATION.]

Among the primary minerals, micas and feldspars are very common in soils, and their weathering rates play important roles in soil formation, in soil fertility and plant nutrition, and in soil chemistry and soil mineralogy.

Micas are basically 2 : 1 structures—they consist of two sheets of silica tetrahedra ($Si_2O_5^{-2}$ repeating unit) bound to each planar side of an octahedral sheet that is usually made up of ions such as Al, Mg, and Fe that are coordinated to O^{2-} and OH^{-1}. These 2 : 1 layers are bound together by large interlayer cations. In K-bearing micas such as muscovite, the interlayer cation is mainly K. Micas are more prevalent in fine-grained sediments and sedimentary rocks (clays, shales) than in coarser textured sedimentary rocks (sandstones).

Some of the more important feldspars in soils are K-bearing (e.g., sanidine, orthoclase, microcline, and acularia). The K feldspar polymorphs are a three-dimensional framework of SiO_4 and AlO_4 tetrahedra, with enough space in the framework to hold K to maintain electroneutrality. The K-feldspar polymorphs comprise about 16% of the total earth's crust, and when they are considered along with alkali feldspars that contain K, the total K-bearing feldspars make up about 31% of the total earth's crust.

Feldspars are usually present in the silt and sand fractions of young to moderately developed soils, representing a number of types of soil-parent material and soil-forming conditions. Alkali feldspars occur in the clay fraction of soils formed under moderate weathering.

Among the secondary minerals, the clay minerals, which are aluminosilicates and which are common in the clay fraction of soils, are most important in affecting the chemistry of soils. A list of some representative clay minerals found in soils, along with some of their important characteristics, is given in Table I.

Clay minerals are composed of silica tetrahedral sheets ($Si_2O_5^{2-}$ repeating unit) bound to octahedral sheets that are made up of ions such as Al, Mg, and Fe that are coordinated to O^{2-} and OH^{-1}. Clay minerals can be classified as either 1 : 1 or 2 : 1, depending on how the tetrahedral or octahedral sheets are arranged.

For example, kaolinite, a 1 : 1 clay mineral, consists of a silica tetrahedral sheet bound to an octahedral sheet. In 2:1 clay minerals like vermiculite, there are two sheets of silica tetrahedra bound to each planar side of an octahedral sheet. Other examples of 2 : 1 clay minerals are montmorillonite, and illite (Table I).

The solid inorganic components discussed previously are crystalline. However, there are amorphous materials in soils. Allophane and imogolite are two amorphous inorganic components of an Al-Si framework. They are found in the clay fraction of soils derived from volcanic parent materials.

Intergrade clay minerals are also found in soils. In acid soils, they are characterized by having hydroxy-aluminum interlayered material.

Other important secondary minerals include oxides and hydroxides such as goethite, gibbsite, and birnessite. Goethite is an Fe-oxide, gibbsite is an Al-oxide, and birnessite is a Mn-oxide. The metal oxides and hydroxides arise by weathering of primary silicate weathering or by hydrolysis and desilication of secondary clay minerals such as kaolinite.

Carbonates and sulfates are also significant solid components in soils and are particularly prevalent in soils of arid regions. In acid soils, sulfates can react with Al and Fe to form minerals such as jarosite, alunite, basaluminite, and jurbanite.

TABLE I
Important Characteristics of Secondary Clay Minerals

Mineral	Type	Chemical formula	Layer charge	Cation exchange capacity (cmol kg^{-1})	Surface area (m^2g^{-1})	Permanent charge	Variable charge
Kaolinite	1:1	$[Si_4]Al_4O_{10}(OH)_8$ $nH_2O(n = O \text{ or } 4)$	<0.01	1–2	10–20	No	Yes
Montmorillonite	2:1	$M_x[Si_8]Al_{3.2}Fe_{0.2}Mg_{0.6}O_{20}(OH)_4$	0.5–1.2	80–120	600–800	Yes	No
Vermiculite	2:1	$M_x[Si_7Al]Al_3Fe_{0.5}Mg_{0.5}O_{20}(OH)_4$	1.2–1.8	120–150	600–800	Yes	No
Mica	2:1	$K_2Al_2O_5[Si_2O_5]_3Al_4(OH)_4$	1.0	20–40	70–120	Yes	No
Chlorite	2:1	$(Al(OH)_{2.55})_4[Si_{6.8}Al_{1.2}]$	variable	20–40	70–150	Yes	Yes
With hydroxide Interlayer		$Al_{3.4}Mg_{0.6}O_{20}(OH)_4$					
Allophane	—	$Si_3Al_4O_{12}{\bullet}nH_2O$	—	10–150	70–300	No	Yes

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B. Organic Components

Important organic components in soils are humic substances. They are naturally occurring, heterogeneous substances that are important in mineral weathering, mobilization and transport of metal ions, sorption of pesticides and other organic chemicals, formation of stable aggregates, and the overall cation exchange capacity of soils. Humic substances can generally be classified as humic acid (not soluble in acid), fulvic acid (soluble in acid), and humin (insoluble in base). The average composition of humic acid is $C_{187}H_{186}O_{89}N_9S$ and of fulvic acid is $C_{135}H_{182}O_{95}N_5S_2$.

III. Soil Mineral Charge

Inorganic and organic soil components can exhibit both permanent and variable charge. Permanent charge arises primarily from ionic substitution when an ion substitutes for another of similar size in a crystal structure. For example, if Al^{3+} substitutes for Si^{4+} in the tetrahedral layer of a phyllosilicate or if Mg^{2+} substitutes for Al^{3+} in the octahedral layer, a net negative charge exists on the mineral. Permanent charge is invariant with pH and is created during the crystallization of aluminosilicates. Smectite and vermiculite are permanent charge minerals.

With variable charged surfaces, such as kaolinite, goethite, gibbsite, and humic substances, the net charge changes with pH and is positive at lower pH and negative at higher pH. The principal source of variable charge on soils is the protonation and deprotonation of functional groups on colloidal surfaces such as hydroxyl (OH^{-1}), carboxyl (-COOH), phenolic ($-C_6H_4OH$), and amine ($-NH_2$). In most soils, there is a combination of both permanent and variable charged surfaces and soil chemical reactions are occurring on both types of surfaces.

IV. Important Soil Chemical Reactions

Many types of reactions take place in soils. Ion association reactions include ion pairing, inner- and outer-sphere complexation, and chelation in solution. Gas–water reactions involve gaseous exchange across the air/liquid interface. Ion-exchange reactions occur when cations and anions are adsorbed and desorbed from soil surfaces by electrostatic attractive forces. Ion exchange is an outer-sphere complexation reaction which is reversible and stoichiometric. Sorption reactions can involve physical binding, outer-sphere complexation, inner-sphere complexation, and surface precipitation. Inner-sphere reactions are these in which a species is bonded directly to a solid without the presence of a water molecule. Such a complex occurs when a metal such as selenite is adsorbed on the surface of a soil mineral such as goethite by exchanging with an OH^{-1} ion or H_2O molecule This is referred to as ligand exchange. Ligand exchange reactions are considered specific and nonelectrostatic. Outer-sphere complexation reactions are reversible, physical, and electrostatic interactions in which the solid remains hydrated and is thus separated from the surface by a water molecule. An example of such a complex is Na^+ adsorption on vermiculite. Mineral–solution reactions include precipitation/dissolution of minerals, and coprecipitation reactions whereby minute constituents become a part of mineral structures.

It should be realized that all of these reactions can occur concurrently and consecutively in soils. Thus, an understanding of soil chemical phenomena in such a system is indeed complex.

V. Modern Soil Chemistry

A plethora of soil chemical studies have been conducted on sorption/desorption processes, ion-exchange reactions, precipitation and dissolution phenomena, oxidation/reduction reactions and other soil chemical reactions. Many of these investigations have been studied strictly from an equilibrium standpoint invoking solubility product principles and empirical, semi-empirical, surface complexation, and ion-exchange models. These approaches have been employed to ascertain a number of parameters including: partition coefficients, binding coefficients, maximum sorption values, intrinsic equilibrium constants, solubility products, and selectivity coefficients.

While these parameters often provide useful information, they are often not applicable to reactions in the field, since soils are seldom, if ever, at equilibrium. Consequently, no rate or kinetic data are derived that would be useful in predicting the fate of metal and organic contaminants in heterogeneous soils with time. Moreover, no definitive mechanistic conclusions can be made. To provide direct molecular information on soil chemical processes, one must employ surface spectroscopic and microscopic techniques.

Accordingly, I will briefly discuss some aspects of what I consider will be extremely important and pioneering areas in soil chemistry for the rest of this century and into the 21st century. My focus is on the kinetics of soil chemical processes and the application of surface and microscopic techniques to the elucidation of reaction mechanisms in soils.

VI. Kinetics of Soil Chemical Processes

One of the most exciting and active fields in soil chemistry today and arguably in the future will be the kinetics of soil chemical processes. The study of chemical kinetics is arduous, even in homogeneous solutions. When one attempts to apply chemical kinetics to heterogeneous soils that comprise an array of inorganic and organic components that are reacting with one another, the complexities are magnified.

Chemical kinetics refers to the study of chemical reaction rates and molecular processes where transport is not limiting. Transport processes refer to the movement of solutes and sorptives in the soil solution, at the soil/soil component interface, and in the solid phase. It is very difficult to eliminate transport in most laboratory experiments, and in the field, transport phenomena often predominate. Thus, they commonly are rate-limiting, i.e., they are usually slower than the actual chemical reaction at a soil surface. Accordingly, in most soil chemistry investigations, one is studying time-dependent phenomena, or the *kinetics* of reactions. [*See* SOIL, CHEMICALS: MOVEMENT AND RETENTION.]

Soil chemical reactions transpire over a range of time scales, occurring from microseconds to millennia. These are illustrated in Fig. 1. The kinetics of soil chemical reactions are greatly affected by the inorganic and organic composition of the soil. The types and amounts of clay minerals, primary minerals, and humic substances substantially affect the rates and mechanisms of soil chemical reactions. Thus, in any kinetic study, one should carefully assess and characterize the physicochemical and mineralogical aspects of the soil or soil component.

Another important aspect of any kinetic study is the type of method that one employs. Several kinds of techniques are used and these can broadly be classified as batch, flow (e.g., stirred-flow and stopped-flow), and relaxation. None of these methods is a panacea for kinetic analyses.

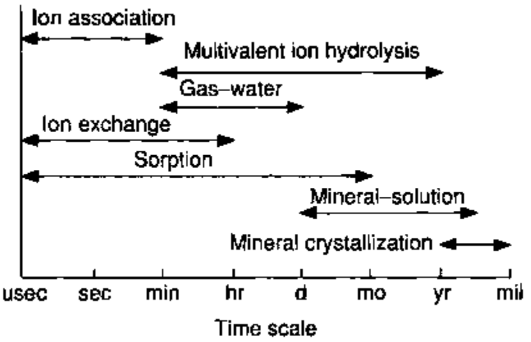

FIGURE 1 Time ranges required to attain equilibrium by different types of reactions in soil environments. [Reprinted with permission from Amacher, M. C. (1991). Methods of obtaining and analyzing kinetic data. *In* "Rates of Soil Chemical Processes" (D. L. Sparks and D. L. Suarez, eds.), pp. 19–59. SSSA Spec. Publ. 27. Copyright © 1991 Soil Science Society of America, Inc.]

Batch and flow methods can be used to measure reaction time scales of seconds or greater. As one can see in Table I, many important soil chemical reactions occur on time scales faster than this. These methods are also often plagued by problems of mixing and thus, physical phenomena are occurring simultaneously with chemical reactions. Thus, the rate parameters that are measured are apparent and dependent on mixing rates.

Relaxation methods can be used to measure reactions on time scales of microseconds and milliseconds. These include such techniques as pressure-jump, temperature-jump, concentration-jump and electric field pulse methods. All of these techniques are based on the principle that a chemical equilibrium can be perturbed by a change in some external parameter such as pressure, temperature, concentration, or electric field and the equilibrium will be slightly perturbed. One can then follow the time that it takes for the system to relax to the new equilibrium state (relaxation time) via a particular detection method such as conductivity. The perturbation is small and thus, the final equilibrium is close to the initial equilibrium. Rate expressions are reduced to first-order equations regardless of reaction order or molecularity and the rate equations are linearized, greatly simplifying determination of complex reaction mechanisms. From the linearized rate expressions, one can plot experimental data and if a linear relation exists, the forward and backward rate constants can be calculated from the slope and intercept of the line, respectively.

In soil chemistry, the pressure-jump relaxation method has successfully been used in our laboratories and in others to study metal sorption/desorption reactions on aluminum and iron oxides and cation exchange kinetics on clay minerals.

In the past decade some important contributions have been made in the following areas of kinetics of soil chemical processes. These include: the development and utilization of kinetic methodologies that enable one to measure soil chemical reactions involving ion-exchange and sorption/desorption on time scales ranging from microseconds to days; elucidation of rate-limiting phenomena for various soil chemical processes; the development of models to describe rates of reactions in heterogeneous systems where chemical reaction and mass transfer kinetics are occurring simultaneously; a greater understanding of metal oxidation kinetics on soil components; and studies on the kinetics of soil weathering reactions.

However, despite advances in the above areas, there are many research needs that must be addressed in the decades ahead to aid in solving environmental soil chemical problems. These are: improvement of kinetic methodologies for elucidating soil chemical reactions over a range of time scales; more sophisticated kinetic analyses of heterogeneous, soil chemical processes; definitive elucidation of interactions of inorganic and organic chemicals with soils by combining kinetic and spectroscopic/microscopic approaches; detailed studies on the kinetics of pesticide, industrial pollutant, and organic waste reactions in soils with particular emphasis on long-term studies; reaction dynamics of humic substances with inorganic and organic contaminants; incorporation of experimentally determined rate parameters into transport models (many of which now assume local equilibrium); effect of macropores on the kinetics of preferential flow of pollutants in soils; effect of mobile humics and other colloids on the kinetics of contaminant reactions in soils; more definitive studies on the oxidation kinetics of metals with soils and soil components; and the kinetics of surfactant-modified clay interactions with organic chemicals.

VII. Use of Surface Spectroscopies and Microscopies

The only way to glean direct information about the molecular and mechanistic aspects of soil chemical reactions is to use surface microscopies and spectroscopies. These techniques can be employed to elucidate surface reaction mechanisms and solid-state species. For example, they can be used to identify the type of interaction that exists or results between soil surfaces and sorbates, e.g., an inner- or outer-sphere complex, surface precipitate, etc., and to assist in speciating contaminants in soils. Thus, their potential use in developing remediation strategies to decontaminate soils and in modeling pollutant interactions so as to minimize pollution of soils and waters is immense.

There are a number of exciting developments in using surface microscopic and spectroscopic techniques to investigate soil chemical processes. However, some of the surface probing techniques are invasive, and they can cause alterations in the surfaces being studied due to the need to: dessicate the sample, place it under high vacuum, heat the sample or bombard the particles. Such treatments can cause experimental artifacts or even prevent experimental analysis. Fortunately, a number of recent advances in surface spectroscopic/microscopic techniques allow an experimentalist to obtain information *in situ*, without subjecting the sample to conditions of drying, high vacuums, etc. Additionally, more extensive structural and chemical information can be obtained with these techniques.

Magnetic and vibrational spectroscopies e.g., electron paramagnetic resonance (EPR), nuclear magnetic resonance (NMR), infrared (IR), and Raman spectroscopies have been used for some time and can provide surface and solid state information under *in situ* conditions. Atomic force (AFM) and scanning tunneling microscopies (STM) have recently been developed and offer innovative ways to investigate soil chemical reactions.

One of the most powerful and useful ways to study reactions on soil components and soils at the atomic scale is to employ X-ray absorption fine structure spectroscopy (XAFS). The energy dependence of X-ray absorption by a material provides information as to the valence and chemical state of the X-ray absorbing species and structural information about its environment, including coordination environments, and in some cases, near neighbor distances. Recently, XAFS has been applied to study metal reactions on metal oxides and clay minerals by geochemists and soil chemists. In our own laboratories, we have used XAFS to elucidate the mechanism for Cr(III) sorption on SiO_2 and to speciate lead contaminants in soils. Without question, the use of this spectroscopic tool, as well as those spectroscopic and microscopic techniques mentioned earlier, will become one of the hallmarks of soil chemistry research.

VIII. Conclusions

An attempt has been made to discuss various historical aspects of soil chemistry, characteristics of soil minerals, development of charge on soil minerals, and important soil chemical reactions. A better understanding of environmentally important soil chemical reactions will be the major thrust in soil chemistry for decades to come. To elucidate the mechanisms of these reactions and to better predict the fate of pollutants in soils will require an increasing application of chemical kinetics and sophisticated surface microscopic and spectroscopic techniques.

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Soil Drainage

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Glossary

Artificial drainage Removal of water from land surface by land forming and open ditches and removal of groundwater by buried or open drains installed below the water table

Drainable porosity Amount of water that can be removed from a unit area of the soil when the groundwater level is lowered a distance equal to unity

Hydraulic conductivity Index of the ability of soil to transmit water

Impermeable layer Layer with very low hydraulic conductivity which impedes vertical movement of water

Leaching requirement Fraction of irrigation water that must percolate below the root zone to maintain soil salinity below a tolerance level for the crop under consideration

Saturated zone Volume of soil where all pores are filled with water and soil water pressure head is ≥ 0

Unsaturated (vadose) zone Volume of soil where pores are filled with both water and air and soil water pressure head is < 0

Water table Upper surface of the groundwater or the upper boundary of the saturated zone where the water is at atmospheric pressure

Soil drainage refers to the removal of water from soil and its replacement by air. Soil drainage is a natural and dynamic process, and it is an integral part of the hydrologic cycle that includes precipitation and evapotranspiration. In soils that do not naturally drain adequately or as rapidly as desired, artificial drainage may be employed to carry excess water out of the soil. In general, soil drainage is a function of many factors including soil properties, climate, and land management.

Soils are considered a three-phase system composed of solids, liquids (water), and gases (air). The water and air phases occupy the pore spaces between the solid particles, and for nonswelling soils their proportions are inversely related to one another. The proportion of water occupying the soil pore spaces can range from near zero in an oven-dried soil to almost 100% in a saturated soil. Water that occupies the pore spaces in the soil is subject to many fates such as evaporation, plant uptake, and drainage. Soil drainage encompasses the downward movement of water to underlying aquifers as well as the lateral flow of groundwater to streams and other surface outlets including springs that may appear on the landscape. In many cases, natural drainage may be adequate to provide a suitable environment for the intended land use. In other cases, removal of water from soil may be enhanced by artificial drainage for land management purposes. [*See* SOIL-WATER RELATIONSHIPS; WATER: CONTROL AND USE; WATER RESOURCES.]

I. Purpose of Drainage

The main purpose of artificial drainage is to provide a better soil environment for the intended land use. In agriculture, drainage is used for enhancing soil conditions for crop production and improving the profitability of farming the land. In addition, drainage may be employed to provide suitable conditions for other land uses such as wastewater application on land, disposal of solid wastes in sanitary landfills, or construction of buildings, highways, and other man-made structures. Surface drainage is also used to elimi-

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nate the environment where mosquitoes and other insects can breed.

In humid regions the goals of drainage by lowering the water content to less than saturation in the upper soil layers are: (1) to facilitate movement of air into the soil and transport of CO_2 and other gases produced by crop roots, microorganisms, and chemical reactions into the atmosphere; (2) to lower the heat capacity of the soil so that the soil warms faster in the spring, improving seed germination; and (3) to improve the trafficability of the soil for timely completion of agricultural operations. The need for artificial drainage depends on the time and amount of precipitation as well as on the rate of natural drainage (i.e., movement of groundwater into natural outlets or deeper aquifers). The need for artificial drainage in areas with high rainfall and good natural drainage may be substantially greater than in areas with low rainfall and relatively poor natural drainage.

In areas where natural drainage is inadequate, irrigation of agricultural lands may result in saturation of the soil (often called waterlogging). In arid and semi-arid regions, where irrigation is essential for agriculture, artificial drainage may also be required for the management of soil salinity. The sources of salts that may accumulate in the root zone are irrigation water, soil minerals (parent material), shallow groundwater with a high level of salt content, and fertilizers or amendments applied to the soil. Accumulation of salts as a result of irrigation in many parts of the world has resulted in the formation of saline and sodic soils. Many fertile agricultural lands have been abandoned due to salt accumulation or waterlogging following irrigation. Concentration of soluble salts in the soil solution increases when irrigation water that is applied to the root zone is removed from the soil by plants and/or evaporation from the soil surface. The result is the eventual build up of salts in the entire soil profile and specifically in the root zone of agricultural crops. To alleviate the problem of soluble salts in the soil, excess irrigation water must be applied to leach the salts below the root zone. If natural drainage is not adequate, water applied for leaching purposes will accumulate in the soil resulting in groundwater (i.e., saturated zone) with a high concentration of solutes. In these soils artificial drainage is needed to remove the excess water and allow leaching of the salts from the root zone. Because of the salinity of groundwater under irrigated areas, the water table (i.e., the top of groundwater) must be kept well below the root zone, therefore requiring deeper artificial drains compared to the humid regions. Proper management of irrigation with artificial drainage can sustain the productivity of many arid lands for agricultural production. [*See* IRRIGATION ENGINEERING: FARM PRACTICES, METHODS, AND SYSTEMS; SOIL FERTILITY.]

II. Surface and Subsurface Drainage

Both natural and artificial drainage can be divided into surface and subsurface drainage. Surface drainage is used to remove water that is standing (or can potentially stand) on the soil surface. Standing water can be due to low permeability of the soil, presence of an impermeable layer at or near the soil surface, and/or a flat topography with surface depressions. Low permeability of the surface horizon or subsurface layers near the soil surface prevents water (mainly from rainfall) from moving into the soil. A flat landscape with or without surface depressions impedes the natural overland flow of rainfall. In some cases, there may not be adequate natural drainage channels (e.g., streams, gullies) to carry the amount of rain falling in an area.

Subsurface drainage is primarily used in areas where excess water can penetrate into and through the root zone, and then move laterally toward a drainage outlet (e.g., a drainage pipe, open ditch). For the reasons mentioned earlier (e.g., low hydraulic conductivity, presence of an impermeable layer, gentle slope), water infiltrating the soil from rainfall or irrigation may not seep into lower aquifers or move laterally to a natural drainage outlet. When excessive water is accumulated in the soil, agricultural operations may be halted and/or plants may suffer from excessive water or lack of air exchange between soil and atmosphere. Subsurface artificial drainage is then needed to remove excess water from the soil. A drainage system may be used to lower the water table over an area or it may be employed to intercept the lateral subsurface flow from adjacent areas.

III. Soil Water Regime and Water Flow

A. Soil Water Content and Soil Water Potential

Soil drainage can only affect a portion of the soil water content and not the entire body of water in a soil system. In soil drainage both the total porosity and the distribution of pore sizes are of interest. The total porosity F (dimensions of volume per volume, L^3 L^{-3}) in the soil is derived from

$$F = 1 - \rho_b/\rho_p, \tag{1}$$

where ρ_b and ρ_p are bulk density and particle density of the soil (dimensions of mass per volume, ML^{-3}), respectively. In general, fine-textured soils (e.g., clayey soils) have a higher porosity than coarse-textured soils. The pores in coarse-textured soils, on the other hand, are generally larger and their distribution narrower than finer-textured soils. In theory, all the pores in a soil are filled with water at saturation. Practically, however, complete saturation may not be achieved due to the presence of entrapped air and variations in pore geometry (e.g., pores not being interconnected). Soil pore size distribution is generally obtained from the relationship between the soil matric potential (pressure head) and volumetric water content. This relationship is called the soil water characteristic or soil water retention curve. The soil water characteristic is not a unique relationship between soil water content and soil water potential because it depends on whether the soil is wetting (i.e., adsorption) or draining (i.e., desorption). This phenomenon is referred to as hysteresis and represents a series of relationships that can be obtained depending on whether sorption (wetting) or desorption (draining) is taking place. Because of the hysteresis and entrapped air, the amount of rise in the water table level when a unit quantity of water enters the water table is higher than the amount of drop in water level when a unit volume of water is drained from the soil.

Soil drainage depends on the energy status of soil water at every point within the soil system. The energy level of water in the soil is generally described by soil water potential. Soil water potential is defined as the amount of work necessary to transfer a unit quantity of water from a reference state to the situation of interest in the soil. Factors that affect the amount of work necessary to make the appropriate transfer are elevation with respect to the reference level, attraction of soil particles and small pores for water (i.e., matric effects), liquid and gas pressures, solute in soil solution, temperature, and overburden pressure. Grouping the pressure and matric potentials together, and assuming isothermal conditions with no solute effect (osmotic potential = 0), the hydraulic head H (i.e., the total soil water potential expressed per unit weight, dimensions of length, L) is given by

$$H = z + h, \tag{2}$$

where z (L) is the elevation above a specified reference level and h (L) is the soil water pressure head. For most field conditions the soil water pressure head (h) is zero or positive for saturated soils, whereas for unsaturated soils h is negative.

B. Soil Water Movement

Water is expected to move from a region of high potential to a region of lower potential in the soil. The rate of water movement is directly related to the hydraulic conductivity of the soil. Hydraulic conductivity is an index of the ability of soil to transmit water, and is perhaps the most important parameter affecting soil drainage. Under saturated conditions almost all the pores in a soil are filled with water, the soil water pressure head (h) is ≥ 0, and hydraulic conductivity, referred to as the saturated hydraulic conductivity (K_{sat}), is assumed to be a constant. Under unsaturated conditions, where h is negative, hydraulic conductivity (K_{unsat}) is a function of soil water content (θ) or soil water pressure head (i.e., $K(\theta)$ or $K(h)$). Both saturated and unsaturated hydraulic conductivities can be measured *in situ* using the soil in its natural state, or be determined in the laboratory using intact or repacked soil columns.

Water movement in soils is governed by Darcy's law

$$\nu = -K\, grad\, H, \tag{3}$$

where ν is the flux density (dimensions of length over time, LT^{-1}), K is the soil hydraulic conductivity (LT^{-1}), and $grad\ H$ is the hydraulic gradient (LL^{-1}). The hydraulic gradient is the difference between the hydraulic head at two points (or regions) under consideration divided by the distance between the two points, and it determines the direction that water will flow.

Water entering the soil surface increases the water content of the upper layers of the soil before being redistributed through the profile. (Note that the presence of macropores such as cracks and root channels that are open to the soil surface may result in rapid movement of water to lower layers or to a shallow water table in that soil.) The process of soil drainage begins with redistribution of water in the profile. Assuming evaporation is negligible (i.e., no upward flux of water) and plant water uptake is zero, the water movement in the unsaturated (vadose) zone would be primarily vertical (i.e., one dimensional). After infiltration of water into soil ceases, water movement within the soil, and hence drainage, continues. Initially, the rate of drainage in the upper soil layers is high. However, as drainage continues, the decrease in water content of the surface layers and the eventual decrease in the amount and size of the pores filled with water result in a substantial drop in the unsaturated hydraulic conductivity. Subsequently, the rate of drainage decreases with time as the soil water content gradually decreases. For example, the rate of drainage in the first few hours after infiltration may be an order of magnitude (i.e., 10 times) larger than the rate of drainage during the second day after infiltration.

To demonstrate the rate of drainage, let us assume that for a deep water table water under no evaporation and no plant uptake moves vertically downward under a unit hydraulic gradient. In this case, the gradient in Eq. (3) is equal to one (i.e., unit hydraulic gradient) through the depth of interest Z^* (L), and the rate of drainage q, i.e., flux at the depth of interest (LT^{-1}), is equal to the K_{unsat}. Assuming an empirical functional relationship for unsaturated hydraulic conductivity of the form

$$K_{unsat} = K_{sat}\exp[\alpha(\theta_v - \theta_s)], \tag{4}$$

where θ_v is the volumetric water content, θ_s is the saturated volumetric water content, and α is an empirical constant, the simple model

$$q = K_{sat}/\{1 + (\alpha K_{sat}t/Z^*)\} \tag{5}$$

can be obtained to describe the rate of vertical drainage past the depth Z^*. Equation (5) is based on conservation of mass, and although simple, it describes the decrease in the drainage rate with time.

C. Soil Water Profile and Drainable Porosity

The patterns of volumetric water content (θ_v) distribution above a deep water table and above shallow water tables in a homogeneous and a layered soil are shown in Fig. 1. For a deep water table, the rate of drainage decreases with time, but drainage to greater depths may continue indefinitely (Fig. 1A). For a shallow water table (at depth Z_0), on the other hand, the drainage ceases when the pressure head and consequently soil water content in the vadose zone reach an equilibrium with the water table (Fig. 1B). For homogeneous soils, soil water distribution in the profile above a shallow water table can be obtained from the distance above the water table and the respective soil water characteristic curve. For a layered soil, the soil water pressure head distribution above the water table will be the same as the one for a homogeneous soil profile. Because of the differences in the soil water characteristic of each layer, however, water content distribution with depth may change abruptly at the boundary between the layers as shown schematically in Fig. 1C. Figure 1C depicts a coarse-textured soil with saturated water content θ_{s1} overlying a finer-textured soil with saturated water content θ_{s2} ($\theta_{s1} < \theta_{s2}$). At the boundary shown in this figure, the soil water pressure heads for the two layers are equal, but the amount of pores filled with water in the upper layer is less than the amount of water-filled pores in the lower layer (i.e., water content of the upper layer is less than the water content of the lower layer).

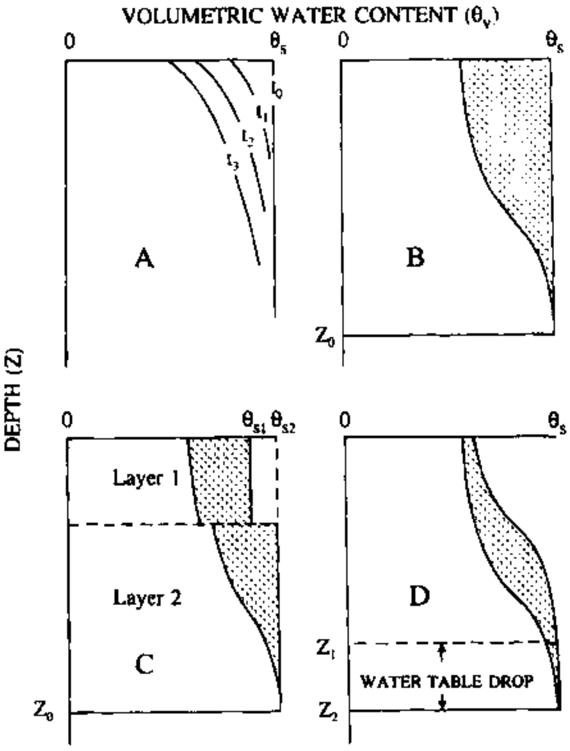


FIGURE 1 Volumetric water content (θ_v) distribution with depth (Z) for (A) a homogeneous profile with deep water table at various times (t_i), (B) a homogeneous profile with a shallow water table (depth Z_0) at equilibrium, (C) a two-layered soil with shallow water table at equilibrium, and (D) two different water table positions (Z_1 and Z_2) at equilibrium. The shaded areas in (B) and (C) represent the total volume of pores that can be drained above the water table, and the shaded area in (D) (the difference between the two water content profiles) is related to the drainable porosity.

The portion of the water that cannot be held in a soil against the force of gravity, i.e., the difference between volumetric water content at saturation and the volumetric water content after the soil has drained, is referred to as drainable pore space (Fig. 1D). Drainable porosity is equated to the specific yield in groundwater hydrology and is defined as the amount of water removed from a unit area of the soil when the groundwater level is lowered a distance equal to unity (i.e., a unit volume of the soil). Drainable porosity can be obtained by plotting the volumetric water contents versus depth for two different water table positions Z_1 and Z_2 (Fig. 1D), and dividing the area between the two curves (shaded area) by the distance between the two water table positions (*i.e.*, $Z_2 - Z_1$). The amount of water held in the soils against the force of gravity may be called field capacity. Because of a number of factors (such as rainfall, evaporation, water uptake by plants, and variation in soil hydraulic properties) equilibrium in water content above a water table may never be achieved in practice.

IV. Water Table

Soil drainage may be impeded when water moving downward through a layer with a relatively high permeability or hydraulic conductivity encounters a layer with substantially lower hydraulic conductivity. Subsequently, water accumulates above the layer of lower hydraulic conductivity resulting in the formation of a saturated zone. From a drainage standpoint, a layer is considered restrictive (frequently referred to as impermeable) when its hydraulic conductivity is an order of magnitude smaller than the conductivity of the overlying horizons.

Hydraulically restrictive layers are caused by many conditions in the soil. The most impermeable ones are high in clay (small pores) or are very dense (low porosity, see Eq. (1)). In some areas relatively thin layers of clay materials may be found within a highly permeable sandy soil. In some other areas, an impermeable layer may be very dense soil that was compressed by overburden pressure during the soil formation. If an impermeable layer extends horizontally over a large area, a permanent saturated zone (commonly called groundwater) may be formed on top of it. For shallow impermeable layers, the water table may readily respond to precipitation and evapotranspiration resulting in fluctuations in the thickness of the vadose zone. Although individual rainfall events may influence the water table, fluctuations are generally noticed over seasons rather than individual events. Thus, the term seasonal high water table indicates a fluctuating water table with high water levels during the rainy season with low evapotranspiration, and low water table levels when evapotranspiration is high and/or rainfall is low. If the horizontal extension of the impermeable layer is limited, then a temporary saturated zone, often called a perched water table, may be formed above that layer. Although a perched water table may not last for an extended period of time (e.g., a season), the presence of an impermeable lens may result in local saturation that may interfere with the intended land use. Also, because the pore sizes in the impermeable lens are much smaller than the pores in the materials above or below it, the lens itself may remain saturated (or near saturated) due to the discontinuity of pore sizes between the lens and the soil above or below it. [*See* GROUND WATER.]

V. Natural Drainage

The geomorphology and landscape position greatly affect the natural drainage and formation of saturated zone or the position of water tables in soils. In areas where the landscape is generally flat with long distances between streams (wide interfluves), the streams act as the natural outlet for most of the precipitation that infiltrates the soils lying between them. If the soils in these areas contain a less permeable (low hydraulic conductivity) layer below relatively permeable (high hydraulic conductivity) materials, deep percolation (i.e., drainage flux in the vertical direction) will be negligible. For these areas, the depth to water table and the degree of water table fluctuation are primarily a function of distance from the streams (or other free surface water bodies such as rivers, lakes or sea) (Fig. 2A). Due to the relatively small slope and large distance to the stream outlets, the horizontal hydraulic gradient is rather small, and drainage flux in horizontal direction will be very low. As a result, the amount of water flowing laterally to streams is limited and soils farther away from the streams have poor drainage conditions. Near the streams, however, the hydraulic gradient is high and water table fluctuations are pronounced with relatively long strips of well-drained soils along the streams.

In areas with rolling landscapes and narrow stream divides soil drainage is substantial at distances away from the streams and lakes (Fig. 2B). Unlike flat areas, the soils near the streams or lakes may have poor drainage while at the top of the landscape position depth to groundwater may exceed a few meters. In general, these conditions are formed due to the slope of the land from the stream to the interfluve. Although hydraulic conductivity may be low to moderate in these soils, a high gradient and shorter distances between the streams allow the water table to remain a substantial distance below the soil surface in most of the landscape positions.

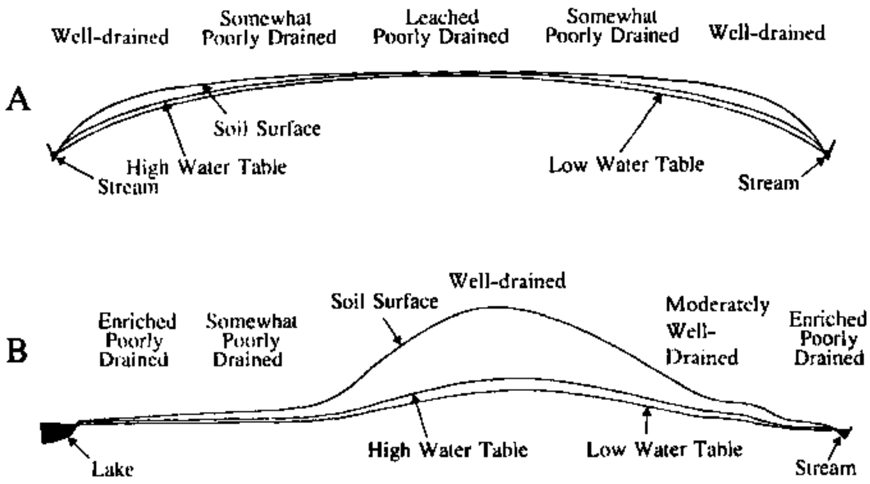


FIGURE 2 Relationships between soil drainage (water table) and landscape position for (A) an area with relatively flat topography and long distance between streams, and (B) an area with rolling topography and relatively short distance between the interfluve and stream. The positions of well-drained to poorly drained soils as well as the leached and enriched areas are shown. [Adapted from *Soil Genesis and Classification*, 3rd ed., by Buol, S. W., Hole, F. D., and McCracken, R. J. © 1989 by Iowa State University Press, Ames, IA.]

Drainage conditions also have a great impact on soil formation. Poorly drained soils are formed in areas where water stands in the soil for a substantial part of the year. In flat areas, poorly drained soils are generally found near the middle of the interfluves, whereas well-drained soils occur near the streams. As indicated in Fig. 2A, the poorly drained soils in the middle of the landscape are generally leached of materials. Conversely, in areas where well-drained soils are formed at the interfluves, enriched poorly drained soils are found near the streams as shown in Fig. 2B.

VI. Artificial Drainage

Whether for controlling the soil wetness in humid regions, or minimizing the impact of salts by leaching them through the soil profile in irrigated arid and semi-arid areas, artificial drainage is used to manage the water table. Both surface and subsurface drainage systems are employed to control excessive water in poorly drained soils.

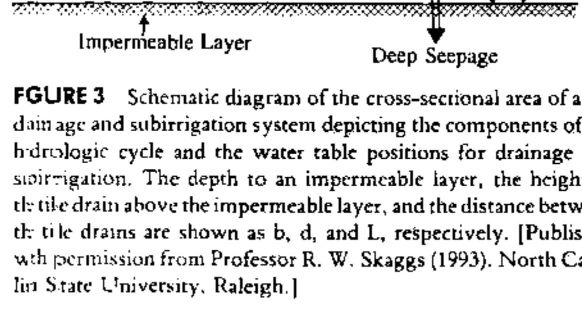
For areas with insufficient surface drainage, construction of open channels and/or land forming to provide adequate slope for overland flow and elimination of depressions may be required. In general, areas with surface drainage problems have many depressions of varying sizes and shapes. Land forming to remove the high spots and filling the low areas can eliminate surface impoundment in shallow depression areas. The larger depression areas, however, may require direct connection to an open ditch. The types of drainage ditch systems include random or natural pattern, parallel, and cross slope or interception drainage.

As discussed earlier, poorly drained soils are generally underlain by an impermeable layer at a relatively small distance below the surface. They may also be located in flat areas where surface drainage is inadequate. When precipitation (or irrigation water) reaches the ground surface, infiltration begins at a rate that is generally greater than the saturated hydraulic conductivity of the soil. As rainfall enters the soil, the water content of the profile increases, and water may start to accumulate above the impermeable layer resulting in a rise in the water table. Depending on the antecedent soil water content, the rate of infiltration decreases with time reaching a final value that is operationally equivalent to the saturated hydraulic conductivity. If the rainfall intensity is greater than the final infiltration rate of the soil, water accumulates at the soil surface. In areas where adequate surface drainage is naturally or artificially available, the excess water moves as runoff away from the area. Otherwise, water remains at the soil surface until infiltration, runoff, and/or evaporation depletes it. If surface drainage is not adequate, water in the depressional areas at the soil surface continues to infiltrate into the soil causing higher soil water content, and in some areas, a rise in the water table level.

To control the water table level the excess water entering the soil must be removed via evapotranspiration, vertical and lateral natural drainage, or an artificial drainage system consisting of tile drains, ditches, and/or wells. In general, an artificial drainage system is composed of various size drains ranging from laterals serving individual fields to main drain lines which carry the drainage water to an outlet. Artificial drainage is accomplished by maintaining the water level in lateral drains that are installed below the water table. The drain tubes (or open ditches) are generally installed at a predetermined depth to allow the water table at the mid-point between two adjacent drain tubes to be lowered a desired distance below the soil surface. This distance is usually selected based on the intended land use. A schematic diagram of the cross-sectional area for a tile drain system in a poorly drained soil showing the positions of the water table for drainage during high rainfall and/or low evapotranspiration and for subirrigation to raise the water level for crop production during low rainfall and/or high evapotranspiration is given in Fig. 3.

Water that is removed by artificial drainage must be eventually disposed of away from the drained area. The final drainage outlet for a field can be a natural body of water or may be channels constructed to facilitate transport of drainage water away from the area. Depending on the topography and land elevation above the final drainage outlet, gravity or pump outlets may be employed to transfer water from drains into the drainage channels or final outlet.

In arid and semi-arid regions irrigation has caused (or may cause) toxic levels of salts (or specific ions such as sodium or chloride) to accumulate in the root zone. Irrigation water generally contains some salt which can accumulate in the soil when water is removed from the root zone by plants or surface evaporation. Depending on the salinity of the irrigation water and the amount of irrigation necessary for an economical crop production, the amount of soluble salts applied annually with irrigation water may range from less than a ton to over 50 tons per hectare. Basically, for every 1 g salt/liter in irrigation water the amount of salts added to each hectare is 100 kg for each centimeter of irrigation water. In general, little of the salt added to the soil can be extracted by plants. To maintain the required salt balance for the cropping system under consideration, the excess salt must be removed from the root zone through leaching. If natural drainage is not adequate, the soil solution containing a high level of soluble salts must be removed by artificial drainage to prevent a build up of salty groundwater reaching the root zone. For salinity control purposes, the depth to water table must be lowered sufficiently to prevent an upward flux of salty water by capillary action into the root zone.



FGURE 3 Schematic diagram of the cross-sectional area of a tile drainage and subirrigation system depicting the components of the hydrologic cycle and the water table positions for drainage and subirrigation. The depth to an impermeable layer, the height of the tile drain above the impermeable layer, and the distance between the tile drains are shown as b, d, and L, respectively. [Published with permission from Professor R. W. Skaggs (1993). North Carolina State University, Raleigh.]

To remove the added salts not used by plants, irrigation water in excess of the crop needs must be applied. The fraction of irrigation water that passes through the root zone is referred to as the "leaching fraction" and is given by

$$LF = D_{dw}/D_{iw}, \tag{6}$$

where D_{dw} and D_{iw} are the amounts of drainage and irrigation waters (commonly expressed as depth of water), respectively. Maintaining the soil water salinity at a constant level and assuming (i) uniform application of irrigation water with no rainfall, (ii) no salt precipitation or plant uptake, and (iii) no salt release from soil minerals or salt transport from shallow water tables under the capillary action, the leaching fraction can also be equated to the ratio of salinity in the irrigation and drainage waters as expressed by the electrical conductivities of the irrigation (EC_{iw}) and drainage water (EC_{dw})

$$LF = D_{dw}/D_{iw} = EC_{iw}/EC_{dw}. \tag{7}$$

Based on the above equation, the concentration of salts in drainage water, and hence the level of salts in the root zone can be controlled at some desirable level (between EC_{iw} and EC_{dw}) by varying LF. The leaching requirement (LR) is defined as the fraction of irrigation water that must be applied in excess of the evapotranspiration needs of the crop under consideration to maintain soil salinity below the tolerance level for that crop. Various models are available to determine the LR based on the salt tolerance of the crop and EC_{iw}. Salt tolerance levels and tolerance levels for certain ions are also available.

A. Types of Drains

Open drains, used in some areas for lateral to main drains, may be considered the most economical means of controlling both surface and subsurface drainage problems. They can be constructed by a wide variety of machinery or be hand-dug, and are capable of transporting a large quantity of water. The open ditches, however, are not efficient for controlling the water table in agricultural fields because of their rather large width and interference with agricultural operations. In addition, the maintenance cost of this type of drainage in areas with high labor cost may prohibit its use. Open drain lines (ditches) may be employed for urban developments in areas with a high water table to control both surface and subsurface waters. An open ditch should have stable side slopes and sufficient flow capacity to remove water at a rate not to cause sedimentation or scouring. The side slope of a drainage ditch depends on the soil texture, and in general, a more flat side slope is required for coarse-textured soils compared to a fine-textured soil with a more stable structure.

Buried drain lines do not generally interfere with agricultural operations and may require considerably less maintenance than open drains. A wide variety of materials and techniques are available for installing buried subsurface drains. The materials include short clay pipes, concrete pipes, perforated plastic or other types of tubings. To prevent inflow of soil particles into the drains (which may result in their clogging) and/or to increase the effective diameter of the drain lines, filter or envelop materials such as gravel may be placed around the drain pipes.

B. Drainage Layout and Drain Slope

The outlet pattern of the lateral drains and their associated main drain(s) depends primarily on the topography of the area to be drained. If waterlogging is confined to a few large depression areas in the field, a random or natural pattern (Fig. 4) in which lateral drains are installed systematically within the depression (wet) areas may be the most effective way of providing drainage. Because of the required number of laterals and their associated collector drains the random or natural drainage pattern becomes less efficient as the size of the depressions decreases and their number increases. When the depressions are scattered throughout the field, or where water table is uniformly high in a large area, a regular pattern such as parallel or herringbone layout (see Fig. 4) becomes more practical.

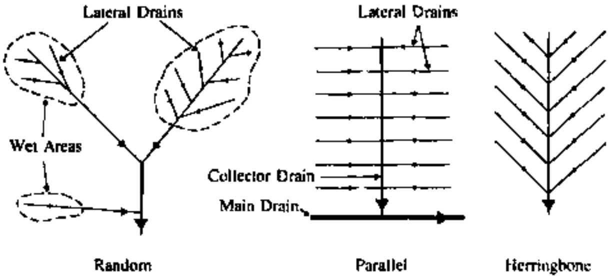


FIGURE 4 Schematic diagram of the plan view of three types of drainage collection system.

The slope of the drain lines should be sufficient to prevent sedimentation in the pipe (provide nonsilting velocity), but should not be too high (causing turbulence) to reduce the efficiency of the system or damage the drains. For lateral drains, and where siltation is not a problem, a slope of 0.05 to 0.10% has been recommended for different size pipes. A higher slope may be used in sloping areas or where siltation is a problem. For sloping areas, the lateral drains may be installed at a slight angle to the contour lines of the land. For flat sites, the desired slope for the laterals must be obtained by adjusting the depth of the drain with respect to the depths of the sub and main drains, and pumping may be required for transferring the drainage water to an outlet.

C. Depth and Spacing of Lateral Drains

The depth and spacing of drain lines depend on many factors including the soil hydraulic properties, the desired distance between soil surface and the water table, depth to impermeable layer, land topography, the amount of water entering the soil via irrigation and/or precipitation, and lateral and upward flow of groundwater. Many mathematical models have been developed to describe water flow into open and tile drains and for determining drainage spacing and depth. The depths at which the laterals and the associated collector drains can be installed are limited by the availability of equipment for installing the lines, the depth of the main drain and outlet, and the topography of the area. In general, the spacings between lateral drain lines can be increased by increasing the depth of the drain lines. Spacing and depth for the lateral drains are generally obtained through an iterative process to calculate the most efficient and yet economical drainage spacing.

D. Subsurface Irrigation

In some soils the subsurface drainage systems can be used for irrigation when soil water content drops below the crop needs. This method of irrigation, also referred to as subirrigation, involves raising the water table above the drains and maintaining it at an appropriate position for providing water to the roots of the growing crops. This is accomplished by damming the open drainage outlet (controlling drainage) and raising the water level above the lateral drains as depicted by the dashed line in Fig. 3. Improvements in the design and operation of subsurface irrigation systems in recent years have increased their use in many areas. To use a subsurface drainage system for subirrigation purposes, certain natural conditions must be present. These requirements include the presence of an impermeable layer or relatively shallow permanent groundwater table within a few meters of the surface, relatively flat land, a moderate to high hydraulic conductivity, and a readily available source of water. Many areas in the humid regions of the United States meet the above requirements.

Perhaps the greatest advantage of the subirrigation/drainage system is the increased ability to manage the water table for crop production. Because both irrigation and drainage are provided through one system, substantial cost reduction can be achieved in areas where seasonal irrigation may be required to maximize yield. Because of the possibility of salt build up, subsurface irrigation is not recommend for arid and semi-arid regions. For humid areas, combining irrigation and drainage into one system requires a careful prediction of the performance of the system through computer simulations.

E. Drainage Models

Various theoretical models based on steady-state and transient water flow conditions are available for drainage design purposes. In general, these models relate tile drain depth and spacing to rainfall and/or irrigation, as well as various soil and site characteristics. Using the models, the drainage rate and the rate of fall of the water table can be determined for an area based on measured and estimated soil and site properties. Simulation models enable the designer of a drainage system to evaluate the future performance of the system under consideration based on several years of climatological data. This will allow optimization of the design parameters to achieve the objectives of the drainage system. For agricultural purposes, drainage designs can be based on the crop(s), soil types, and locations.

Available theoretical models include those with rigorous approaches for modeling soil water movement based on saturated and unsaturated flow in two or three dimensions. Although these models can provide valuable information about soil water with time and space, water table position, drainage, and subsurface irrigation, they are generally complicated and may require numerical evaluations. The complexity of solving the problem numerically, and the difficulties associated with determining the required soil input parameters for unsaturated flow conditions limit the use of complicated models. To overcome the problems associated with analytical and numerical models, a number of user friendly simulation models have been developed. One of the less complex approaches has been the development of the DRAINMOD model that is based on water balance in the soil profile. This simulation model includes methods to simulate surface and subsurface drainage, surface irrigation and subirrigation, and controlled drainage. The data required for this model include soil properties, crop parameters, climatological information, and drainage and irrigation system criteria. This model can be used to simulate the performance of both drainage and irrigation systems over an extended period of time according to known climatological data. The major advantages of this model are the ease of use and the relatively minimal computational requirements as compared to other approaches. The model has been tested for a wide range of soils, crops, and climatological conditions with good results.

F. Water Quality

Drainage waters may carry agricultural chemicals and other solutes present in soil solution to surface waters resulting in undesirable water quality. Enhancing runoff to improve surface drainage may result in transportation of suspended soil particles and soluble chemicals to surface waters making them undesirable for drinking water, fishery, or recreational purposes. In this regard, transport of chemicals attached to soil particles is of great concern. In subsurface drainage to control soil salinity, the quality of drainage water may not be suitable for discharge to a body of water or reuse as irrigation water. In humid areas, the nutrient loading of the drainage water may result in degradation of water quality in streams and lakes. For example, it has been shown that phosphorous from agricultural fields travels mainly by surface drainage while the main transport mechanism for nitrogen is subsurface drainage water. To minimize the impact of agricultural water management on the quality and quantity of ground and surface waters, consideration of the soil drainage must be an integral part of any agricultural operation.

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Soil Fertility

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Glossary

Mineralization Process by which organic materials are decomposed and inorganic ions are released

No-tillage Management practice in crop production whereby all residues (excluding grain) are left on the soil surface without incorporation

Nutrient sufficiency Degree to which the nutrient supply approaches 100% of the plant requirement

Volatilization Release of gaseous forms into the atmosphere generally referring to ammonia losses from urea and anhydrous ammonia nitrogen fertilizers

The science of soil fertility examines the availability of essential plant nutrients in soils and their effect on growth, composition, and yield of plants. Scientists in this field develop fertilizer application technologies that make prudent use of natural resources and that protect the environment.

I. History of Soil Fertility

Ever since Justus von Leibig (1803–1873) stated the mineral theory of plant nutrition, scientists have been interested in whether elements were essential, the nature of their available forms in soil, and the relationships between the amounts of these available forms and plant growth. The development of the science of soil fertility has depended heavily on this knowledge. Thousands of scientists have contributed to our understanding of how soils should be managed and how organic and inorganic fertilizers should be used to maximize yields and limit environmental contamination. Two thousand years ago, Virgil (70–19 B.C.) encouraged the use of legumes in crop rotations, and he also understood soil acidity as it relates to crop production. Pietro de Crescenzi (1230–1307) is considered by some to be the founder of modern agronomy via his work that encouraged increased use of manures. Since that time, numerous scientists have added to our knowledge of soil fertility via the discovery of essential elements, chemical sources of these elements, and appropriate methods of application.

The development of soil science got off to a slower start in America than it did in Europe, partly because of the abundance of land that could be exploited for its native fertility. Because of the vast areas available, the need was less urgent for maintaining the fertility and productivity of the soil. It was easier to move West. Bradfield stated that

> A worker in the field of soil fertility must have a good understanding of the general principles of soil physics, chemistry, microbiology and pedology. I like to think of soil fertility as the highest development of science. It must be built upon the information supplied by these other fields. None of the others are concerned primarily with the growing of plants. Because of the very nature of our subject, we are primarily concerned with integration and synthesis of these other fields.

As the science of soil fertility has progressed, we have come to appreciate how much has been accomplished and how important this knowledge is to feeding our increasing world population. [*See* Soil Chemicals: Movement and Retention; Soil Chemistry; Soil Genesis, Morphology, and Classification; Soil Microbiology.]

II. Soil–Plant Relationships

Justus von Leibig was probably the first scientist to explain the nature of soil fertility. He stated that the nutrient present in the least relative amount is the limiting nutrient for plant growth. This law implied that all the other nutrients were present in excess until the deficient or limiting nutrient was in adequate supply, whereupon the one present in the next least relative amount became the deficient nutrient and so on.

Work by E. A. Mitscherlich established that plant growth follows a diminishing increment type of curve now known as the yield curve. In his work it is assumed that every plant species has a finite growth possibility when all nutrients and growth factors are adequate but not in harmful excess. Baule concluded that when more than one nutrient was deficient, the final percentage sufficiency is the product of the individual sufficiencies. Supposing that soil potassium is adequate for 90% of a yield and phosphorus for 80%, then the final yield is 72% of the yield obtainable when both nutrients were adequate (100%). The sufficiency level of available nutrients (SLAN) concept is based on a general mathematical expression of the law of diminishing returns where increases in yield of a crop per unit of available nutrient decreases as the level of available nutrient approaches sufficiency. The concept implies that (1) levels of available nutrients range in a group of soils from insufficient to sufficient for optimum plant growth, (2) amounts of nutrients removed by suitable extractants will be inversely proportional to yield increases from added nutrients, and (3) calibrations have been made for changing the levels of available nutrients in the soil by adding fertilizer (or lime).

Work by Bray identified two distinct types of sorption zones for plants. One is the large volume of soil occupied by the major part of the plant root system (root system sorption zone) from which mobile nutrients are taken up by plants. The other sorption zone is a relatively thin layer of soil adjacent to each root surface (root surface sorption zone) from which immobile nutrients can be removed by the plant (Fig. 1). This concept has assisted many researchers in the development of appropriate methods of applying fertilizers depending on whether the nutrient elements are relatively mobile or immobile in soils.

III. Essential Plant Nutrients

More than 100 chemical elements are known today. However, only 16 have proven to be essential for plant growth. Early work by Arnon and Stout noted that there were three criteria which had to be satisfied in order for an element to be classified as essential for plant growth: (1) the plant cannot complete its life cycle without it; (2) no other element can take its place; and (3) the element must be directly involved in the plant's nutrition and not indirectly through correction of some other unfavorable condition in the soil or release of some other essential element.

The essential plant nutrients, chemical symbols, mobility in the soil and plant and general deficiency symptoms are listed in Table I. Three of the essential elements (carbon, hydrogen, and oxygen) are used in relatively large amounts by plants and are considered nonmineral since they are supplied to plants by carbon dioxide and water. The other 13 essential elements are mineral elements and must be supplied by the soil and/or fertilizers. The essential plant nutrients can be grouped into three categories which are as follows: (1) Primary nutrients, nitrogen (N), phosphorus (P), and potassium (K). (2) Secondary nutrients, calcium (Ca), magnesium (Mg), and sulfur (S). (3) Micronutrients, iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), molybdenum (Mo), and chlorine (Cl). Nutrient deficiencies tend to express varied symptoms in the plant and therefore should be used with caution, especially if more than one element is limiting. In general, mobile nutrients in the plant tend to induce chlorosis in the older leaves. Alternatively, immobile nutrients in the plant cause the deficiency symptom to appear in newer leaves (Table I).

IV. The Nitrogen Cycle

Because nitrogen deficiencies have historically been more common, this nutrient has also received more attention in research. A thorough understanding of the nitrogen cycle is essential for those involved in soil fertility work. Following Leibig's law of the minimum, if this nutrient is deficient, all others will be adversely affected. Nitrogen is an integral component of amino acids which are the building blocks for proteins. Proteins are in turn present in the plant as enzymes that are responsible for metabolic reactions in the plant. Noting the complexity of nitrogen in soils, Allison stated the following:

> Many things can happen to nitrogen in the soil. There are so many possible transformations that can lead to gaseous products, or to the formation of soluble forms of nitrogen that are subject to leaching, that it is little wonder that recoveries in the crop may sometimes be

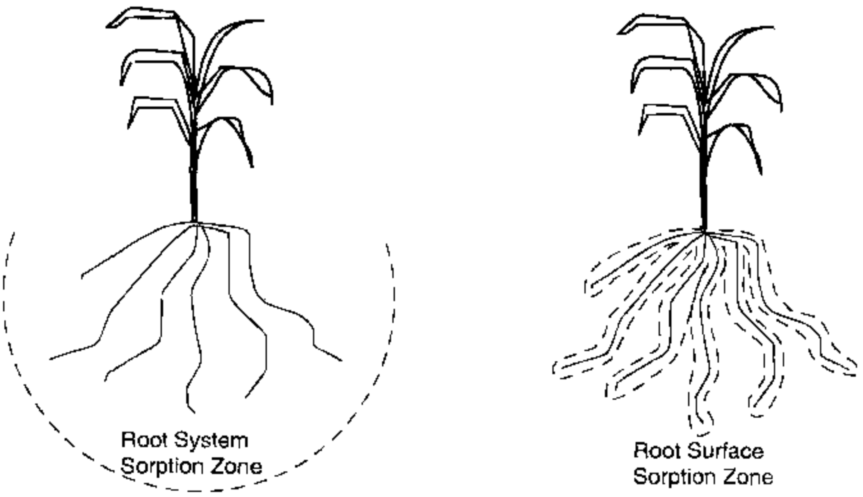

FIGURE 1 Root system and root surface sorption zones identified by R. H. Bray to explain the areas where mobile and immobile nutrients will be taken up by plants, respectively.

low. But it is well not to overemphasize these possible losses for, fortunately, under conditions of good management most of the worst possibilities can usually be avoided. [*See* NITROGEN CYCLING.]

Most of the nitrogen in continuously cultivated soils is present as organic nitrogen in the soil organic matter (Fig. 2). In temperate climate soils, there is approximately 2000 kg of N for every 1% of organic matter in the surface horizon (0–30 cm). Soils in many of the northern parts of the United States and southern Canada contain in excess of 4% organic matter and can have over 8000 kg N/ha stored in organic pools. Not surprisingly, the supplying power of this soil organic N pool must be considered in making N recommendations in crop production systems. Under frequent cultivation, approximately 2% of the total nitrogen in soil organic matter will be mineralized each year. Cultivation alone unleashed a radical change in soil N dynamics and in organic matter composition of soils. Various long-term experiments that have been conducted for more than 100 years have documented the decrease in soil organic matter which

TABLE I

Essential Plant Nutrients, Chemical Symbols, Mobility of Elements in the Soil and Plant, and Chemical Form Taken up by Plants

Deficiency symptom	Element	Mobility in the soil	Mobility in the plant	Form taken up by plants
Overall chlorosis seen first on lower leaves	N (Nitrogen)	Yes	Yes	NO_3^-, NO_2^-, NH_4^+
Purple leaf margins	P (Phosphorus)	No	Yes	HPO_4^{-2}, $H_2PO_4^-$, H_3PO_4
Chlorotic leaf margins	K (Potassium)	No	Yes	K^+
Uniform chlorosis, stunting (younger leaves)	S (Sulfur)	Yes	Yes	SO_4^{-2}, SO_2^a
Stunting—no root elongation	Ca (Calcium)	No	No	Ca^{2+}
Interveinal chlorosis, veins remain green	Fe (Iron)	No (ls)	No	Fe^{3+}, Fe^{2+}
Interveinal chlorosis	Mg (Magnesium)	No (ls)	Yes/No	Mg^{2+}
Reduced terminal growth = chlorotic tips	B (Boron) (NM)	Yes	No	$H_3BO_3^0$
Interveinal chlorosis	Mn (Manganese)	No	No	Mn^{2+}, Mn^{4+}
Wilting, chlorosis, reduced root growth	Cl (Chlorine)	Yes	Yes	Cl^-
Young leaves, yellow & stunted	Cu (Copper)	No (ls)	No	Cu^{2+}
Interveinal chlorosis in young leaves	Zn (Zinc)	No (ls)	No	Zn^{2+}
Interveinal chlorosis, stunting	Mo (Molybdenum)	Yes/No (ls)	No	MoO_4^{-2}
Dark green color	Na (Sodium)	No (ls)	Yes	Na^+
	C (Carbon)			CO_2
	H (Hydrogen)			H_2O
	O (Oxygen)			H_2O

Note: NM, nonmetal; ls, low solubility. Mo availability increases with soil pH, other micronutrients show the opposite of this.

[a] Absorbed through plant leaves.

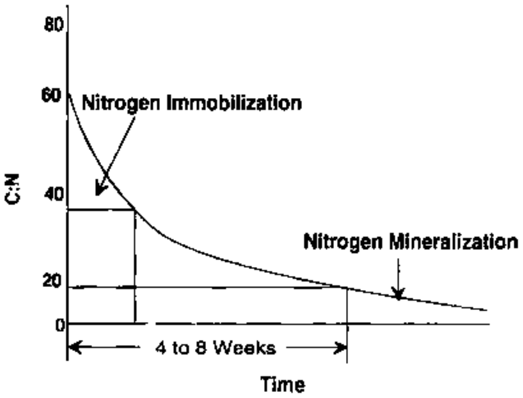

FIGURE 2 Narrowing of carbon to nitrogen ratio as organic matter decays until mineral nitrogen finally becomes available via mineralization.

has been the direct result of continuous cultivation. Unfortunately, many research institutions have discontinued some of their long-term continuous corn and wheat experiments which over time have provided accurate estimates of sustainable production systems.

Because nitrogen release from organic matter is dependent upon decay by microorganisms, which themselves require mineral nitrogen, the amount of mineral nitrogen available for a crop is in constant flux. Nitrogen availability depends upon the relative amount of carbon and nitrogen in the organic matter, its resistance to decay, and environmental conditions to support microbial activity. Figure 2 illustrates how nitrogen becomes more concentrated as soil organic matter decays with time. Nitrogen is not released during the first stages of decay because it is immediately consumed by active microorganisms. With time, remaining organic material becomes more resistant to decay, microorganisms die off, and there is more mineral nitrogen present than can be consumed by the few active microorganisms.

Prior to the time when the native prairie soils in North America were cultivated, N proceeded through the same cycle that is understood today. However, many of these processes took place at much slower rates. Mineralization (combined process of releasing inorganic N from organic N pools), ammonium fixation (ammonium ions bound within clay fractions of the soil), organic immobilization (ammonium and nitrate consumed by microbial organisms), plant volatilization (loss of N as ammonia gas from the leaves of plants), denitrification (microbial transformation of nitrate to gaseous N forms), and leaching (movement of nitrate and or other mobile compounds through the soil profile) all took place for thousands of years before these soils were cultivated. Background levels of nitrate in soils are therefore not uncommon but rather the result of a natural time consuming process.

Nitrogen is added to the N cycle when fixed from gaseous N in the atmosphere by lightning and various symbiotic and free-living microorganisms and additions of inorganic and organic fertilizers. The major sources of plant available nitrogen loss within the N cycle include: (1) volatilization, (2) immobilization, (3) gaseous plant loss, (4) denitrification, and (5) leaching. Immobilization does not result in a net loss but is used in this discussion to reflect removal of inorganic N from plant available forms. It is important to note that nitrate leaching in most crop production systems can only take place once inorganic N has bypassed each of the first four categories (Fig. 4).

1. Additions of fertilizer N can initially be lost by volatilization. Losses of fertilizer N as ammonia (NH_3) generally occur on high pH soils. Applications of fertilizer N (especially urea) on the surface without incorporation on soils where surface residues are present will magnify ammonia volatilization losses.
2. Immobilization of fertilizer N will take place in virtually all soils by both microbial consumption and formation of highly stable lignin–N compounds. Microorganisms will not multiply and organic matter will not be decomposed unless nitrogen is assimilated into microbial protoplasm, and assimilation will take place as long as there is microbial activity. A common phrase used among soil microbiologists is that "the microbial pool eats at the first table." In other words, the demands of soil microflora are met prior to the time crop N uptake occurs. This is important since the majority of all microbial activity takes place in the surface soil horizon (0–15 cm) where plant root volumes are greatest.
3. Once the plant consumes inorganic N, gaseous N losses from the plant as NH_3 are known to take place.
4. When excess N is neither consumed by the aerobic microbial pool and/or the crop, facultative anaerobes (generally present below 30 cm) are involved in the denitrification of inorganic N (Fig. 4).
5. Finally once inorganic N is not volatilized, fixed by the soil, immobilized in organic pools, consumed by the plant, or denitrified by facultative anaerobes, leaching of N as nitrate can take place (Figs. 3 and 4). Many comprehensive N cycles fail to illustrate this point since they show microbial immobilization as taking place simultaneously with leaching (Fig. 3). In the absence of the first four nitrogen sinks, it is likely that groundwater

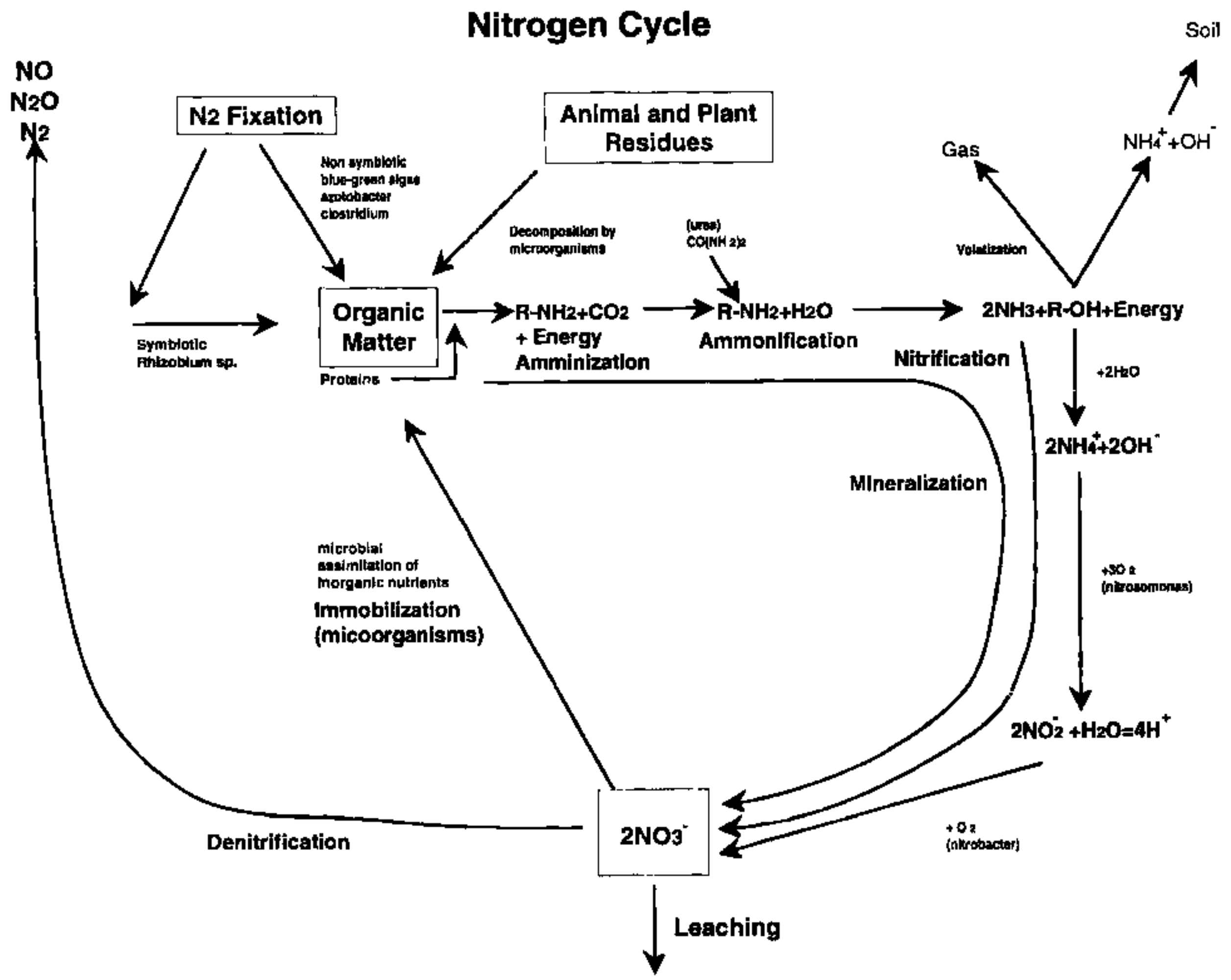

FIGURE 3 Comprehensive nitrogen cycle for plant–soil relationships.

levels of NO_3-N would be considerably higher than found today.

V. Soil Organic Matter, a Key to Nutrient Management

One hundred years ago, most of the native prairie soils in temperate climates had soil organic matter levels in excess of 4%. Today, following 100 years of continuous cultivation, these soils now have organic matter levels less than 2%. Under annual, frequent cultivation, decomposition of soil organic matter exceeds its formation. This continuous cultivation of soils greatly affects the organic matter nutrient supplying power, which in return has an important bearing on both the physical and chemical characteristics and response in crop yields. Organic matter influences structure, and affects aeration, drainage, water-holding capacity, and erosion.

When our forefathers first tilled these soils, there were no fertilizer needs because of the nutrient supplying power that had been stored within the organic matter fraction and the small demands of low yield potential crops. However, today, inorganic and organic fertilizers are needed to supply the nutrients required for economically sustainable crop yields. Excluding nitrogen, phosphorus, and potassium, even the depleted soil organic matter pool present today continues to provide adequate supplies of micronutrients for continuous corn and wheat for the vast majority of soils in the grain belt. [*See* FERTILIZER MANAGEMENT AND TECHNOLOGY.]

Although this resource has been mined, it is seldom understood that organic matter contents in soils can be increased by various management practices. Increased

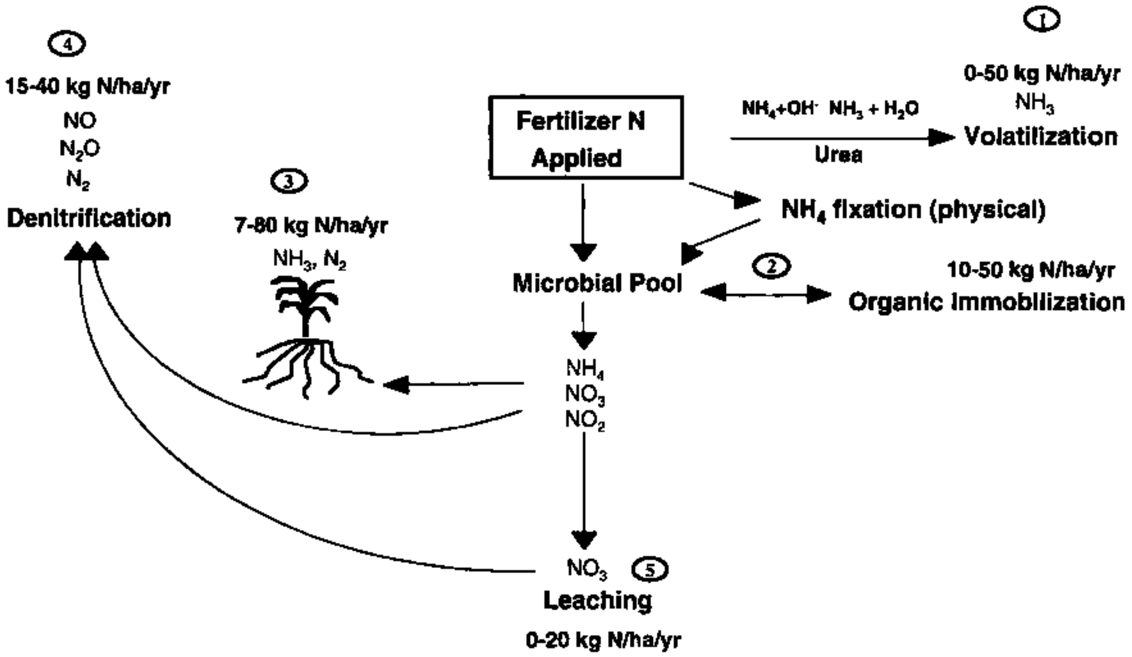

FIGURE 4 Fate of inorganic nitrogen in soils describing losses that can exist in crop production prior to nitrate leaching and general amounts lost from each sink in continuous crop production systems.

use of no-tillage management practices can increase soil organic matter. Soil scientists have demonstrated that the long-term use of no-tillage in continuous crop production systems results in increased surface soil organic matter levels. Similarly, nitrogen fertilizer applied at rates in excess of that needed for maximum yields can also result in increased soil organic matter levels via increased total biomass production. Crop management systems that include rotations with high residue-producing crops and maintenance of surface residue cover with reduced tillage also can result in greater soil organic matter, increased total soil N, and improved soil productivity.

VI. Soil Testing

Soil testing is considered to have started with Justus von Leibig's work in 1840. The aims in soil testing are to assess the relative adequacies of available nutrients (and lime requirements) and to provide guidance on amounts of fertilizers (or lime) required to obtain optimum growth conditions for plants. These objectives are dependent upon obtaining representative soil samples, analyzing them using the appropriate methods, and calibrating the effects on crop response (or increased soil test values) of added units of fertilizer (or lime) to soils at various initial levels of available nutrients. The inclusion of lime in this discussion points to the importance of soil pH in all soil testing procedures and ultimate nutrient recommendations. Soil pH is generally determined from a 1 : 1 soil : water mixture whereby hydrogen ion concentrations (activities) are inversely related to the resultant pH value. In general terms, measured pH reflects the acidity or basicity of a soil which in turn can affect crop production. [*See* SOIL TESTING FOR PLANT GROWTH AND SOIL FERTILITY.]

Total soil analysis (determining the entire amount of a nutrient in soils) for soil testing purposes has been almost completely abandoned except to confirm the absence or very low total reserves of an element. However, total soil N is still used to some extent for predicting availability. In the 1920s and early 1930s, soil scientists' attention turned to displacement of the soil solution with organic solvents, water, and compressed air. Such studies showed that the soil solution did not contain enough N, P, K, and other elements to sustain plants very long, and so the mineral and organic phases must be important in continually replacing the solution phase. This development led chemists and soil scientists to use weak solvents such as CO_2-saturated water and dilute acids in an attempt to imitate what the plant might be able to extract from a given soil. The total amounts in soil could not reflect when and where a deficiency could occur because much of this was bound (in the clay fraction or within organic matter pools) in unavailable forms.

Various extracting solutions have been developed over time that quantitatively assessed the nutrient supplying power of soils for a particular element. Major modifications of how these extractants are used for specific soils have improved our ability to predict when and where nutrient deficiencies will take place. Soil testing is an all-encompassing program that can be divided into four stages: collecting soil samples, extracting and determining the index of soil fertility, interpreting the analytical results (indexes), and making the fertilizer recommendations. First, a population of samples is needed to establish the given nutrient deficiency with corresponding yield data. Second, the program must then establish field trials at respective locations where nutrient levels are considered deficient, moderately deficient, and not deficient. At these sites, fertilizer rates are applied and crop response determined for a given soil test level. Once enough data have been collected optimum fertilizer rates can be determined (recommendation) for a particular soil test level (index) using the defined extracting procedure. While much of the research in soil testing has focused on developing chemical procedures for evaluating the levels of available soil nutrients, techniques for relating soil test results to crop yield response have been equally important.

An example of soil analysis and resultant percentage yield is illustrated in Fig. 5. Percentage yield for this example would be the yield obtainable at a given soil test P level when all other nutrients were present in adequate amounts. In this example, two distinct statistical methods are listed that are commonly used to detect the critical level (point at which an increase in soil analysis no longer results in an increase in yield). The critical level determined using quadratic and linear-plateau methods was 92 and 52, respectively. Given these large differences, it becomes apparent that not only is the soil analysis method important in determining critical levels, but also the statistical method applied to identify the critical test level of the research data. If a soil sample from a farmers field were taken, the correlation response data in Fig. 5 would be used to decide whether P was deficient in the soil. A fertilizer rate recommendation (assuming the P level was deficient) would then be generated from field data where grain yield response to applied P had been previously determined.

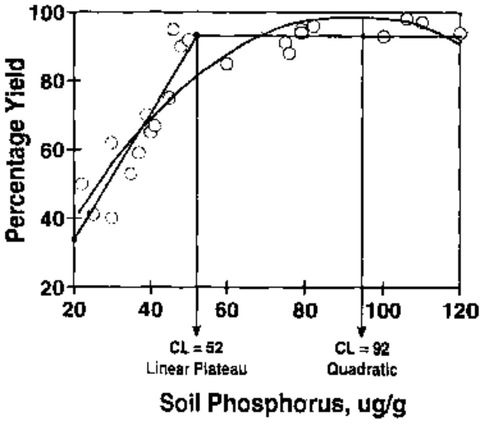

FIGURE 5 Critical soil analysis levels determined using linear-plateau and quadratic functions. CL = critical soil test level below which applied phosphorus fertilizer would be recommended to achieve maximum yields.

Almost without question, improved soil testing procedures for phosphorus and potassium have contributed more toward the efficient use of these elements. This has been largely due to the common need for P and K fertilizers and also because more research has been conducted on these elemental deficiencies.

VII. Fertilizer Sources and Methods of Application

Over the years, soil scientists have conducted thousands of experiments evaluating various methods of applying nutrients to soils. Historically, most fertilizers have been sold in granular forms and have been broadcast and incorporated prior to planting. However, in the interest of efficiency and economy improved methods of fertilization have been developed. Phosphorus, which is an extremely immobile nutrient in soils should be band applied (localized placement) when soil test levels are low and when economics dictate the application of low rates. This method of application is also recommended for soils which have high phosphorus fixation capacities. Soils derived from volcanic ash have extremely high phosphorus fixation capacities, and therefore, band applications improve effectiveness by limiting the surface area of the fertilizer in contact with the soil. Research has demonstrated that broadcast applications (uniformly applied on the surface with or without incorporation) of phosphorus decreased the efficiency of this fertilizer on soils where fixation capacities were high. Improved methods of application and fertilizer sources for correcting iron deficiencies in plants have also been developed. Because this element is immobile in the soil and most fertilizer materials quickly react in the soil and become unavailable, foliar applications of iron sulfate solutions continue to provide the best results when iron deficiencies are present.

With the development of liquid fertilizer sources, altered methods of application have become necessary. The most common nitrogen source used today is anhydrous ammonia, which is a gas, but is sold as a liquid under pressure. This source, which contains 82% nitrogen must be injected beneath the surface of the soil in order to limit gaseous losses. Today, it is common for other liquid sources to be applied jointly with anhydrous ammonia within the same band. Most recently, soil scientists have developed techniques to fertilize specific portions of an entire field based on differences in soil test indices (variable rate technology). In the past, farmers applied a given fertilizer rate based on the average nutrient deficiency for an entire field; however, variable rate technology allows the farmer to apply more fertilizer where it is needed and less where nutrient deficiencies are small. As has been the case in other scientific fields, improved fertilizer use efficiency has come as the result of hundreds of research years dedicated to improving methods, and the development and evaluation of improved sources.

VIII. Future Needs

Many developing countries have traditionally used various kinds of organic materials to maintain or improve the productivity, tilth, and fertility of their agricultural soils. However, several decades ago organic recycling practices were replaced with chemical fertilizers applied to high-yielding cereal grains that responded well to high levels of fertilizers and adequate moisture. Along with the failure to implement effective soil conservation practices, the agricultural soils in many developing countries have seriously degraded and declined in productivity because of excessive soil erosion and nutrient runoff and the decrease in stable soil organic matter levels. Soil scientists are continually developing agronomic solutions to these problems while constantly evaluating alternative production systems that are economically sustainable.

Although organic farming research (crop production without the use of commercial fertilizers) has been instrumental in decreasing inputs, it cannot sustain present world population food needs nor is it a viable alternative for the future. It has been estimated that an overnight switch from the use of commercial fertilizers to organic farming (use of manures, compost, etc.) would result in net food production levels of one-fourth that required for man today. Technologies are present today that will ensure environmentally safe and economically sustainable crop yields for future generations; however, these technologies require commercial fertilizer inputs. As the world population grows, the science of soil fertility will be challenged with improving nutrient management and fertilizer use efficiency on a total world land area that is continually shrinking. Production areas in the developed world cannot sustain future world populations without the continued development of appropriate sustainable technologies for developing nation lands.

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Soil Genesis, Morphology, and Classification

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I. Soil Genesis
II. Soil Morphology
III. Soil Classification

Glossary

Clay Solid particles less than 0.002 mm in diameter
Pedology Collective term more frequently used in Europe than in the United States referring to the science of the ground
Sand Solid particles 0.05 to 2 mm in diameter
Silt Solid particles 0.002 to 0.05 mm in diameter

Soil genesis, morphology and classification are subdivisions of pedology. Soil genesis deals with the factors and processes that are responsible for the formation of soils at the earth's surface. Soil morphology encompasses the measurement of soil properties such as color, structure, and chemical and mineralogical composition. Soil classification is the categorization of soils into groups according to systems devised by people and reflecting their understanding of soil morphology and/or presumed genesis. Numerous soil classification systems are in use. Each system reflects the specific objectives of originators of the system to organize the continuum of soil properties naturally present for specific practical uses of soil, or more universally, to aid in remembering properties and communicating these properties from individual to individual and preserving them in the scientific literature. A closely related subject, not included in the article, is soil survey. Soil survey is an integrated activity of classifying soils and representing the spacial distribution of different soils at a reduced scale on a map. [*See* SOIL AND LAND USE SURVEYS.]

I. Soil Genesis

The thin, usually less than 2- or 3-m-thick layer of the earth's surface not covered by water is nature's meeting place of organic and inorganic chemistry. It is also the meeting place of solids, the mineral components of the earth's crust, and the gases of the earth's atmosphere. In addition, this thin layer interacts with all of the precipitation falling upon it causing that precipitation to run off over its surface, be filtered through that layer to the underlying groundwater, or be temporarily retained to be extracted by the roots of vegetation. [*See* SOIL DRAINAGE.]

A. Factors in Soil Genesis

The degree to which each of these factors affects the thin near surface layer of the earth's surface, henceforth called soil, is best presented in the following state factor equation:

$$S = F\,(P,\ C,\ O,\ R,\ T).$$

In this often used expression, S is the resulting soil properties; F is an integrating function of P, the initial solid minerals of the geologic material; C includes all the climatic conditions primarily temperature and precipitation; O represents all organisms that live in and on the soil; R is the relief or topographic factor mainly including the slope of the soil surface; T is the time within which the other factors are able to alter the morphology of the soil.

Although the state factor concept of soil genesis is academically valuable in conceptualizing why soil morphology differs from one place to another, it provides little insight into how soils form. A more complete understanding of soil genesis can be obtained by examining the processes that can take place within the soil during its formation and use.

B. Processes of Soil Genesis

Conceptualizing soil as an open system within which changes take place and where matter and energy are

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both entering and leaving can be done in Fig. 1. Here a volume of soil is portrayed with its surface interfacing with the air, its lower boundary is at an undetermined depth but below the deepest extension of plant roots, and it is bounded on either side by other soils.

1. Energy Exchange

Except for minor amounts of heat coming from the internal mass of the earth, soils heat and cool from the surface. Heating and cooling have a daily cycle in most soils that extends to a depth of about 50 cm. Annual temperature changes take place to depths of several meters.

2. Water Exchange

In most soils water enters through the surface. Water also is lost from the surface by evaporation if the soil is not covered by vegetation but more often through transpiration from growing plants. The exchange of water, although represented as cyclic, is sporadic with entry during rainfall and loss at other times. Some entry may take place under deep snow packs when the soil is not frozen and in some soils with little rainfall exchange is minimal for long periods during the year. In some soils water also enters the soil by lateral groundwater flow from adjacent soils. [*See* SOIL–WATER RELATIONSHIPS.]

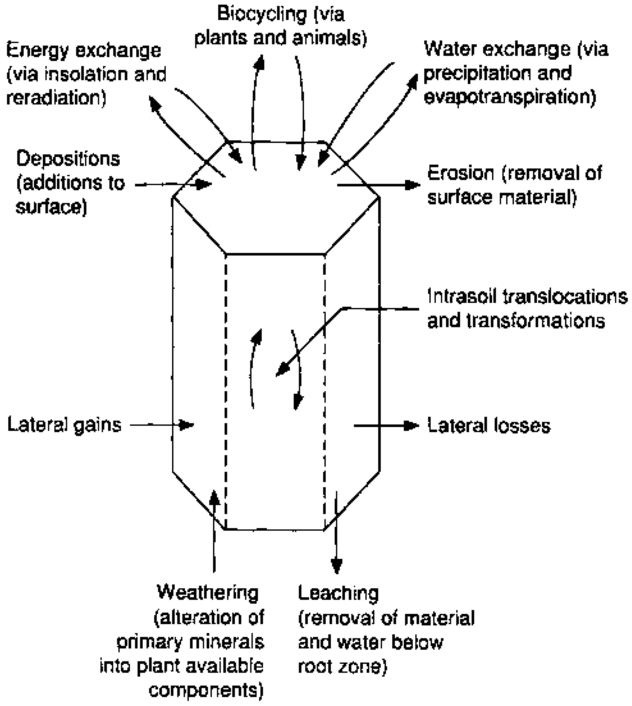

FIGURE 1 Schematic representation of soil as an open system. [Reprinted with permission from Buol, S. W., Hole, F. D., and McCracken, R. J. (1989). "Soil Genesis and Classification." 3rd ed. Copyright © Iowa State Univ. Press, Ames.]

3. Biocycling

Vegetation growing on soil is a key factor in defining soil from geologic material. During the life cycle of vegetation, it captures inorganic forms of plant-essential elements through its roots and transports them to its aboveground parts. Upon the death of the aboveground parts, these same elements are deposited upon the surface. Animals may enter this picture by eating some of the vegetation but the ultimate fate is the same, except that animals, especially humans, often transport the elements to another site, thus breaking the cycle portrayed. Plants and some of their associated microorganisms also obtain carbon, in the form of carbon dioxide, from the air and thus add it to the soil to be lost again as a gas or in solution as the organic compounds decompose.

4. Erosion and Deposition

In response to the energy available from the force of falling raindrops, the solid mineral particles at the soil surface may be suspended and be moved to another location. That other location very often is another soil. Thus, erosion or removal of soil material from one soil results in deposition on another soil. Of course, some soil material is totally removed to the oceans or deeply buried in lakes. Erosion and deposition are key processes in understanding soil genesis because their actions clearly point out that the surface of the soil is not stable throughout time. During the long time spans within which soils form, the proverbial firm foundation is either going up or going down. The amount of time involved is highly variable and often sporadic as in flood or landslide events.

5. Intrasoil Translocations and Transformations

An analysis of the water exchange process reveals that in most soils, in a reasonably warm climate and actively supporting vegetation, most of the rainfall is lost by transpiration. Soluble and suspendable materials move rapidly downward during the rainfall. Between rainfalls much of the water stored in the soil is taken up by the plant roots. Plant roots are selective membranes and ingest only those dissolved elements the plant needs for its life cycle. Particles such as clay or organic particles, suspended near the soil surface during a rain event, are left to accumulate in the subsoil. As the subsoil dries during the rainless periods, mostly by plants transpiration, clay and other water-translocated materials excluded by the plant roots form coating on larger mineral grains or root channels or precipitate as rather insoluble forms. Thus, many but not all soils have greater contents of clay, iron, carbonate, and other mobile compounds in the subsoil than in the surface. Organic compounds go through a multitude of transformations during this downward trek, thereby loosing identity with the organic forms deposited on the soil surface from decaying organisms.

Not all the activity represented in the open system figure forms layers in the soil. Roots, insects, burrowing animals, and volumetric shrinking and swelling of some soil particles as they wet and dry physically mix materials within the soil. The magnitude and type of intrasoil transformations and translocations differ greatly from soil to soil. A detailed discussion of these processes is beyond the scope of this article.

6. Lateral Gains and Losses

No soil exists as a single entity. Each soil has other soils surrounding it and materials can flow from one soil to another. This is most evident on hillsides where the lower part of the soil is less permeable than the upper part of the soil. When this situation exists, infiltrating water flows from one soil to another carrying with it suspended solids and more commonly soluble salts.

7. Leaching

In the context of soil genesis, leaching refers to the removal of material to such a depth that it cannot be gathered by the plant roots and cycled via biocycling. In most respects, this represents material originating in or passing through the soil and entering the regional groundwater. Although there is possible reentry into another soil, perhaps as seepage at the base of a slope, leaching is strictly a loss from the soil. In arid regions leaching may be a sporadic event or never occur. In such regions subsoils accumulate even the most soluble materials at the maximum depth of water penetration. [*See* SOIL, CHEMICALS: MOVEMENT AND RETENTION.]

8. Weathering

The inorganic minerals that now find themselves near the earth's surface (i.e., in the soil) almost all formed at higher temperature and pressure within the cooling magma of the earth's crust. Thus, many of them are quite unstable and soluble in the soil water. As they decompose, many of their elements become ions in the soil solution and in this form are available for uptake by plant roots. Essentially all the elements required for plant growth, except nitrogen, carbon, hydrogen, and oxygen, come from the weathering of minerals. Some soils are forming in materials relatively rich in plant-essential nutrients, such as glacial deposits and volcanic ash, whereas many soils form from quartz sandstones or iron oxides that contain almost no plant nutrients. In the latter case, the resulting soil has very limited mineral reserves from which to derive plant-essential elements. Although Fig. 1 represents weathering as entering the soil volume from the bottom, in some cases aerosolic dust or flood depositions can input weatherable minerals at the surface. Also, human activity of adding mineral fertilizer, which in some soils has been taking place for several hundred years, can be conceived of as a mechanism for contributing weatherable minerals to a soil.

II. Soil Morphology

What we see, feel, and measure within a soil is included in morphology. What we see should not be limited to the resolution of the naked eye and considerable literature exists on the subject of micromorphology, a branch of soil morphology that employs optical and electron microscopes to observe the association of clay particles, bacteria, and other microscopic features in the soil.

A. Soil Horizons

As has been discussed in the factors and processes of soil genesis, soil is a relatively thin layer separating the geologic and atmospheric components of the earth. Thus, it is natural that although being only a couple meters thick, soil like other "skin tissues," is organized into discrete layers. These layers within a soil are called horizons.

The surface, or uppermost layer of a soil, is where most of the organic residue from biocycling is placed. It therefore usually has the highest concentration of organic compounds and a black or darker color than layers deeper in the soil. Also, all of the water that infiltrates into the soil passes through the surface, so small particles of clay size tend to be removed from this surface horizon. The darker color is simply organic compounds in various stages of decomposition.

By convention surface horizons are referred to as A horizons if the organic carbon content is less than 12% or O horizons if they contain more than that amount of organic carbon. A popular term, but having no adequate scientific definition for such horizons, is topsoil.

In many, but not all soils, there is a lighter colored horizon immediately under the A horizon. This results mostly in forested soils where almost all of the clay and iron oxide have been removed by percolating water. Because almost all the organic matter additions have been on the surface by leaves from the vegetation, this horizon contains little organic matter. This horizon is conventionally called the E horizon to connote eluviation.

Under the A and E horizon, where present, is what is commonly referred to as the subsoil. By convention subsoils are referred to as B horizons. There are numerous kinds of B horizons and they have only one of two genetic interpretations in common. The most simple of B horizons are identified because they have evidence of more mineral weathering than the underlying parent material. This is usually identified by some red or yellow colors indicative of iron oxide released when primary minerals in the parent material weathered in the near-surface environment.

The other and perhaps more familiar genetic connotation of a B horizon is that of a horizon of illuviation. It is the subsoil layer that is the repository of soluble and/or suspendable material eluviated by percolating water from the A and E horizons, but left to reconstitute as water is extracted by plant roots. Depending upon the type of mineral or organic material eluviated from the above horizons, the B horizon is enriched, relative to the parent material in clay, iron oxide (hence red color), organic matter (hence black color), or carbonate (hence white color).

Under the A, E, and B horizons is the material that shows characteristics indicating it has been relatively unaltered by soil-forming processes. By convention, if the material is friable enough to dig with hand tools, it is called a C horizon. If it is hard rock, it is called an R horizon.

B. Common Intrinsic Soil Properties

A complete listing of all the components modern soil scientists are able to observe and measure in a soil is well beyond the scope of the article. Suffice to mention that all of the naturally occurring chemical elements are present in soil. Soils are the recipients of all the organic substance produced by plants and animals and these substances decompose in the presence of all the inorganic components known to occur in geological minerals. These organic and inorganic derived components are further mixed by every kind of microorganism capable of living in temperature and moisture conditions present in soil. Since the total number of morphological features of a soil is almost infinite, only a few of the more commonly determined features are presented. [*See* SOIL MICROBIOLOGY.]

1. Particle Size Distribution

Often referred to as texture, this is a measurement of the relative amounts of sand, silt, and clay in a soil sample. This is probably the most useful measure of a soil and its various horizons. Soils with a high proportion of sand have large voids between the particles. All soils have about 50% void space, although this can vary by several points above or below this value. Voids in a soil, commonly called pores, are alternately filled with water or air. Water must pass through these pores when entering the soil or as it is "sucked" to a plant root. Medium-sized pores, sometimes called "capillary pores," hold water against the force of gravity and thereby provide the water plants need during rainless periods. Silt size particles provide this size pore.

Soils with a high portion of their mineral material in clay size have very small pores that hold a great amount of water, but because the pores are so small, water does not easily flow to a plant root. Even though clay soil may contain water, the plants may wilt or die because of their inability to obtain that water fast enough. Very fine organic matter has this same characteristic.

2. Soil Structure

Soil material is not a uniform homogeneous mixture of sand-, silt-, and clay-sized particles. Clay-sized particles adhere to each other and to larger particles. Often particles of any size may be cemented by organic and/or inorganic gels that are quite insoluble. This heterogenous distribution of particle size and cementing agents creates a network that cannot be identified by a simple determination of the amount of sand-, silt-, and clay-sized particles. Also, structure is created and destroyed by pressure as in tillage or simply walking on a wet soil. Roots force their way through soil creating continuous holes which persist after they die and decay. Structure and the most important feature of structure, the continuity of pore space or channels for water and air, are very dependent on a variety of factors including the activity of organisms, roots, and water content. Conditions of structure, while visible in soil samples, are subject to change upon any manipulation of the soil material.

3. Soil Color

This most obvious morphological feature of soil is also a very good indicator of several soil chemical and mineralogical properties. Within local areas soil color serves quite well as a communication tool but on a global basis it is entirely inadequate to represent soil properties. Three basic colors bear relationship to significant soil properties. Black usually identifies a high content of organic matter, although there are black-colored minerals that can belie this interpretation. Also, a high organic matter content can be colored red by iron oxide, in which case any quantitative evaluation of organic matter content by quantification of black color has only local significance.

The red and yellow colors are significant and quite reliable indicators of well-aerated, oxidized conditions in the soil. The red to yellow colors reflect the presence of iron oxides. Red is very indicative of hematite while yellow indicates goethite. These minerals can persist in soil only when they are not solubilized by reduction. Reduction takes place in soil when it is saturated with water for several days when the temperature is high enough for microbial respiration. This saturated and chemically reducing condition removes the iron leaving the silicate minerals uncovered. Mixtures of silicate minerals, whether they be sand, silt, or clay, are gray color. Thus, a gray-colored soil usually indicates that water saturation and reducing chemical conditions are present at least part of the year. Gray to white colors can also be caused by the presence of carbonate so again it is necessary to examine soil color in greater detail to verify what causes that color.

4. Chemical Morphology

Except for the few hints of soil chemistry that can be obtained from soil color, it is necessary to analyze soil to determine its chemical properties. Chemical analysis of soil is extremely complicated by most chemical standards. The difficulty arises from two inherent features of soil. First, every known element is likely to be present in soil; thus, extracting only the element or compound selected for determination is subject to all kinds of interference and contamination. Second, it is seldom informative to determine only the total content of a particular element. Most of the elements of practical interest in soil are present in several chemical forms and only some of these forms have significance in relating the soil quality to a particular use such as growing plants. [*See* SOIL CHEMISTRY.]

A discussion of soil chemical morphology is well beyond the scope of this article and the reader is referred to the references of methods of soil analysis for further information. [*See* SOIL TESTING FOR PLANT GROWTH AND SOIL FERTILITY.]

III. Soil Classification

Classifying soils has probably been informally done by people working with the soil well before any written communication was available. Black soil, red soil, dry soil, wet soil are but a few common expressions that serve within local communities to express the experience individuals have had with various parts of the land they occupy.

Because soil is geographically fixed, it has only become possible to attempt truly global classifications of soil, based on measured soil properties, since the advent of rapid global transportation. Earlier attempts to express soil properties were based upon concepts related to theories of soil genesis. Names used in these early attempts, such as Lateritic, Alluvial, Podzolic, and Latosol, are so morphologically qualitative that conversion to modern systems is inaccurate at best and most often misleading. They must be considered obsolete.

A. Natural Classification Systems

At present there are two natural classification systems that attempt to reflect soil properties on a global basis. The UNESCO/FAO world soil map project, started in the 1960s, produced a 1 : 5,000,000 scale map of the world and defined 106 quantitatively defined names for their map units. Although a remarkable advancement in the understanding of soil on a global basis, this work has, unfortunately, not been vigorously expanded. The small number of broadly defined kinds of soil, while serving as a reference among soil scientists around the world, is inadequate to express soil differences at a detail needed to work in individual fields.

Beginning in the 1950s there was an effort by the Soil Survey Staff of the U. S. Department of Agriculture and faculty from the Land Grant Universities in the United States to develop a soil classification system that could include all soils in the world as their properties became known through research. This effort, most formally presented as Soil Taxonomy in 1975, continues. It is a comprehensive system that is constantly being refined to accommodate new findings and especially new methods of quantitatively analyzing soil. At present about 16,000 kinds of soil are defined within the United States and a worldwide estimate is not available. Although Soil Taxonomy and, to a lesser extent, the World Soil Map legend of UNESCO/FAO have worldwide acceptance and are used as standards in the scientific literature, many countries find it desirable to develop unique systems for classifying only the soil within their country. Although these efforts hinder global dissemination of information, they often provide a more satisfying mode of communication among small nationalistic groups of earth scientists concerned with soil-related sciences within that country.

B. Soil Taxonomy

The recognition by the originators of this system that any soil classification system must grow to accommodate new information, but not destroy itself in the process, stands as perhaps the most innovative feature of the system. It is a hierarchical system of six categories with each of the highest four categories defined by a syllable (formative element) in the composed name.

At present there are 11 orders, the highest category in the system. A complete presentation of the system is not possible in this article but the following example may convey the essential features of the system.

It is essential that use of the system follows the key, which contains the quantitative limits of properties permitted in each category. Attempts to classify a soil at any given level in the system, without following the key, often lead to errors.

1. Outline of the Keys to Soil Taxonomy

The reader is cautioned that the following outline is drastically abbreviated and presented only to demonstrate the form of the system. No classification is possible using only what is presented.

The categories that form the hierarchical system are Order, Suborder, Great Group, Subgroup, Family, and Series.

Abbreviated criteria in key to orders	Order name
Organic soils	Histosols
Other soils of volcanic ash	Andisols
Other soils with humus/amorphous subsoils	Spodosols
Other soils with oxide rich subsoils	Oxisols
Other soils with extreme shrink swell properties	Vertisols
Other soils with less than 90 days of moisture	Aridisols
Other soils with acid subsoils	Ultisols
Other soils with thick, dark colored surface	Mollisols
Other soils with slightly acid subsoils	Alfisols
Other soils with weak subsoil development	Inceptisols
Other soils	Entisols

There are two points the readers should note in the abbreviated key. First, the key must be followed sequentially. If the soil being classified meets the requirements of the third order, the subsequent orders are not considered and the user goes immediately to the keys within the Spodosol order. Second, in formulating the name for lower categories, a syllable beginning with a vowel in the order name (underlined) becomes the last syllable as the total name is formulated. For Spodosol, this is od.

2. Abbreviated Example of a Suborder Key

Within each of the 11 orders, there is a key to the suborders of that order. Staying with the Spodosols, the following crudely approximates the key to its suborders:

Abbreviated suborder key (Spodosols)	Suborder name
Spodosols that are saturated with water	Aquods
Other Spodosols with six times more iron than carbon	Ferrods
Other Spodosols with iron/carbon ratio <0.2	Humods
Other Spodosols	Orthods

Note that the formative element has connotations of the criteria. Aquods are wet, Aqua from Latin, i.e., water; iron-rich Spodosols use Ferr, from Latin ferrum, i.e., iron; humus-rich Humods from Latin humus, i.e., earth; and Orth connotes the true or common, from the Greek, Orthos.

3. Abbreviated Example of a Great Group Key

To continue within the Spodosol order, the Aquod suborder is used as an example of the keys to great group:

Abbreviated great group key (Aquods)	Great group name
Aquods with a brittle subsoil	Fragiaquods
Other Aquods too cold to grow crops	Cryaquods
Other Aquods with a hard Si-rich subsoil	Duraquods
Other Aquods with a hard iron-rich subsoil	Placaquods
Other Aquods in the tropics	Tropaquods
Other Aquods with very little iron	Haplaquods
Other Aquods	Sideraquods

The formative elements used are: Fragi, from Latin fragilis, i.e., brittle; Cry, from Greek Kryos, i.e., icy cold; Dur, from Latin durus, i.e., hard; Plac from Greek plax, i.e., flat stone; Trop for tropical; Hapl for Greek haplous, i.e., simple; Sider from Greek sideros, i.e., iron.

4. Abbreviated Example of a Subgroup Key

Using the Sideraquods great group as an example, the following divisions are made for the subgroup category:

Abbreviated subgroup criteria (Sideraquods)	Subgroup name
Sideraquods with organic surface layers	Histic Sideraquods
Other Sideraquods with high pH in subsoil	Alfic Sideraquods
Other Sideraquods with clayey subsoils	Ultic Sideraquods
Other Sideraquods with coarse subsoils	Entic Sideraquods
Other Sideraquods	Typic Sideraquods

Note that the correct name of the subgroup includes the great group name and that the subgroup name is an adjective form. The above examples indicate that the subgroup has certain defined properties that cause it to be somewhat like soils in the Histosol order (Histic); the Alfisol order (Alfic); the Ultisol order (Ultic); the Entisol order (Entic); or Typical of the great group Sideraquods (Typic).

5. Family Category

To complete the formal name through the family category, each soil is named for selected criteria not used in any of the higher categories. These criteria differ depending on the criteria already used.

For most, but not all soils, criteria of particle-size distribution in the subsoil, the mineral composition of the subsoil, and the soil temperature are used. For example, a family name for one kind of Spodosol can be:

Histic Sideraquod; sandy, siliceous, frigid

6. Series Category

Within the United States and in some other countries, further subdivisions are made within each of the families. Criteria used depend upon differences not previously used in the higher categories. It is important to observe that a series must have properties that are within the ranges defined by all of the higher categories, but are defined as different from other series within the same family by some additional criteria. Approximately 16,000 soil series are recognized in the United States at this time. No worldwide estimate can be made.

Series names traditionally are selected to reflect a city or other place near where that soil was first defined. For example, the Miami series, classified as Typic Hapludalfs, fine-loamy, mixed, mesic, was named in 1910 for Miami, Ohio. The series name is the most frequently used designation of soils on detailed soil maps. Higher category names are frequently used for small-scale maps.

C. Technical Classification

While Soil Taxonomy and other systems previously mentioned attempt to classify soils using all properties that can be consistently measured, there exists a multitude of technical classification systems. These systems classify soils according to specific criteria critical to a specific soil use or a particular legal designation. Common examples at this time are various health department criteria defining soils suitable for septic systems and soils not suitable for septic systems. Such technical classifications are subject to change as the regulatory rules change and will be different from one area of the country to another. While they may in many cases mimic the criteria used in Soil Taxonomy, they are not part of the more universal or natural taxonomic systems such as Soil Taxonomy or the UNESCO/FAO system.

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Soil Management

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Glossary

Conservation tillage Tillage method or sequence that leaves a protective cover of crop residue on the surface that can reduce soil or water loss compared to leaving the soil bare

Crop residue Portion of plants left in the field after harvest such as stems, leaves, or possibly pods or cobs

Fertilizer Organic or inorganic material that is added to the soil to supply elements essential to plant growth. It may be either naturally occurring or manufactured. Ammonia and urea are sources of nitrogen that occur naturally in animal manure but are also manufactured because the supply from manure is limited

Manure Solid or liquid animal waste often mixed with waste feed or bedding. Can be an important source of plant nutrients

Organic farming Production of plants or animals without the use of manufactured inputs such as fertilizer, pesticides, etc; often relies on the recycling or importing of nutrients in plant residue and animal manure

Seedbed Soil prepared by natural or artificial means to promote the placement and germination of seed and growth of seedlings

Soil fertility The ability of the soil to provide 14 essential nutrients such as nitrogen, phosphorus, copper, etc., in proper balance to plants

Soil organic matter The organic fraction of the soil that includes plant and animal residues at various stages of decomposition but generally smaller than 2 mm in diameter

Soil quality The ability of a soil to function in its immediate environment for a particular use and interact positively with the general environment

Soil tilth A qualitative term describing the physical state of the soil. It indicates the ease of tillage, seedbed preparation, seedling emergence, and root growth. It may also indicate the ability of the soil to resist erosion. The best condition for seeding wheat may not be the best condition for growing cranberries

Tillage The operation of machines through the soil to prepare seedbeds and rootbeds, control weeds and brush, manage crop residue, aerate the soil, and cause faster breakdown of organic matter and minerals to release plant nutrients

Soil management is a broad and inclusive collection of human activities, including tillage practices, cropping sequences, cultural practices, organic waste applications, and other physical, chemical, or biological manipulations that are undertaken to work with or improve soil for an intended use such as food, feed, or fiber production.

I. Why Manage Soil?

A. To Grow Food, Feed, and Fiber

The principles of good soil management are universally applicable. They apply in tropical regions of Asia, Africa, or South America just as they do in temperate parts of Asia, Europe, or North America. Developing good soil management practices is important for irrigated lands as well as for rainfed areas. They are important for forest soils and grassland regions as well as those areas used for crop production. Though different from those used for agriculture, soil management strategies are also important for land uses including road construction, building sites, human and animal waste disposal, or recycling operations, or almost any other activity that occurs on the earth's surface. This article, however, focuses on soil management practices that are applicable to crop production.

Techniques and practices of soil management vary greatly from country to country, region to region within a single country, or even from field to field within a locality. The management practices that are best for the problem(s) to be solved in one area may be inappropriate for another area because of differences in soil, climate, capital, human resources, or other factors. Furthermore, practices that are optimum for solving a particular problem in a particular locality may actually change over time because of changes in crops, agricultural amendments or fertilizers, and machinery. For this reason, soil management cannot be effectively discussed in terms of final solutions. The challenge, therefore, is to develop a broad understanding for the variety of practices that should be considered when attempting to correct or prevent some particular problem such as soil compaction, acidity, low fertility, inadequate drainage, or an inability to accept and retain water received through rainfall or irrigation.

Good soil management may be defined as the handling of soil and crops in a manner that ensures crop yields are optimum for the soil and water resources available and that the soils will remain suitable for crop production for an indefinite period. Soils will be kept in good condition for crop production by adhering to three principles of good soil management: namely maintenance of good physical, chemical, and biological conditions. The maintenance of good physical conditions generally refers to maintaining satisfactory soil structure. This is important because of its effect on plant root growth, water relations, and aeration. Maintenance of good chemical conditions usually involves the addition of essential plant nutrients including nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, boron, copper, iron, manganese, and zinc; adjustment of the soil pH to an optimum range of approximately 5.0 to 8.0 by addition of limestone or occasionally (and primarily for specialty crops) acid-forming materials such as sulfur; and sometimes the removal of toxic materials. Maintenance of a favorable biological environment under field conditions generally only requires that an adequate amount of carbon be provided to sustain the micro- and macrofauna and that toxic substances be used judiciously. With this general overview of soil management with regard to production of crops, several specific practices and reasons for their use are examined.

The interaction of plants and soils is required for production of food, feed, and natural fibers consumed or used by humans and other animals. Soils with little or no management provided food for relatively small populations of humans represented by hunting–gathering societies. Archeological studies indicate that tillage was probably first employed in Iraq. As humans domesticated plants and animals, they also began to manage soil through practices, such as tillage and plant selection, to increase yields. A stone hand sickle, presumably used to harvest grain, and other stone implements found at an excavation site in Iraq are thought to have been buried sometime near 11,000 B.C. As civilization expanded, soil management was a key ingredient that led to the production of more food for larger populations.

The origins of many principles of soil management lie hidden in unrecorded history; however, many of the practices used today were also used several thousand years ago. Techniques such as adding manure, lime, and rotating crops have been used for centuries. The Romans had some very excellent agricultural practices as documented by the poet Virgil (30 B.C.) who wrote about rotating crops. Earlier still, Cato (234 to 149 B.C.) told of the benefits of lucerne (alfalfa) in crop production. However, after the downfall of Rome, the practice of crop rotation declined and was actually lost. This was consistent with the loss of most intellectual pursuits in Europe during the "Dark Ages" and therefore resulted in many people living for nearly 1000 years in a frustration of disease, famine, and war.

B. To Remove Limitations to Plant Growth

Higher soil productivity depends on developing management practices that remove or prevent plant growth limitations. These barriers might be physical, such as a very dense or compacted soil layer(s) that is difficult for roots to penetrate; chemical, characterized by the presence of excessive amounts of aluminum or manganese or insufficient amounts of calcium; or biological, if the soil lacks the appropriate microbes such as rhizobium strains that infect plant roots, but then enable them to fix and thus use atmospheric nitrogen gas (N_2) for their growth.

Physical barriers to plant growth are often removed by using tillage. A very visible example of this can be found along the Atlantic and Gulf Coastal Plain in the southeastern United States where deep tillage is used to disrupt a natural hardpan that forms below normal tillage depth because of the size distribution of soil particles and low organic matter concentrations. Unless shattered mechanically, this dense layer restricts plant root growth and prevents the plants from using the entire soil profile to meet its needs for water and nutrients. Even with conservation tillage practices which preserve crop residues near the surface, in-row subsoiling is needed on an annual basis for efficient and profitable crop production.

The application of lime can frequently be used to increase soil pH and thus reduce concentrations of aluminum and manganese which can be toxic to plant roots. The addition of essential plant nutrients through commercial fertilizers or organic sources such as compost, municipal sludge, or animal manure can be used to eliminate many of the chemical barriers to crop production.

Addition of crop residues, manure, or other carbon-containing materials in conjunction with appropriate inoculation of crops such as alfalfa or soybean with the desired species of microorganisms or control of pathogenic microflora is generally sufficient for removing most biological limitations to plant growth. Depending on your point of view, insects, weeds, and some diseases may be biological limitations to plant growth but they can come from parts of the environment other than the soil.

C. To Protect the Soil Resource

Soil resources must also be managed to protect or repair them from damage caused by inappropriate uses or adverse environmental conditions. Soil erosion, which involves detachment, transportation, and deposition of soil materials by wind or water, is one of the primary factors that can deteriorate soil resources. Erosion occurs naturally at a geologic rate, but man's activities often hasten the loss by several orders of magnitude. Agricultural production is responsible for much of the increase in erosion rates, but land uses including road construction, mining, and urbanization also affect soil losses. Management practices that reduce the impact of raindrops, reduce the quantity and velocity of surface water flow, or increase the resistance of the soil to degradation through dispersion and slaking are important strategies that must be developed and used to sustain and improve soil resources.

A renewable resource is one that is produced naturally and continually. Sunlight, at least within a human time scale, is renewable, while petroleum and coal are generally thought of as nonrenewable resources. Soil is a very slowly renewable resource and can be damaged to the point that it is essentially nonrenewable. It should be protected to ensure that we are able to sustain food, feed, and fiber production into the future. Management practices that sustain or improve soil resources are thus extremely important.

II. How Can We Manage Soil?

A. Manipulation of the Physical Environment

Most plants have a relatively broad range of soil conditions that they can tolerate and a smaller range in which they thrive. The primary physical conditions which affect plant growth include soil texture, depth, structure, temperature, aeration, and water content. Soil texture provides an indication of the relative amounts of sand, silt, and clay size particles that are found mixed together in a particular soil. For road or pond construction, golf courses, or other urban land uses, it may be possible to change soil texture in limited areas by adding large quantities of sand or clay materials. However, it is generally not practical to change soil texture for agricultural purposes. In humid areas, medium- to fine-textured soils are generally considered to be the most productive. Coarse sands or very fine clays present many problems to plants growing on them. Sandy soil tends to be infertile because of leaching and low water retention, while very fine textured soils tend to be slowly permeable and poorly drained. Soil depth, up to a point, determines the soil volume which will be available for plant roots to explore. Thus, any gravel lens, natural hardpan, tillage pan, or subsurface bedrock that reduces the depth of useable soil material may restrict plant growth. [*See* SOIL FERTILITY; SOIL GENESIS, MORPHOLOGY, AND CLASSIFICATION.]

Soil structure, which generally refers to the arrangement of soil particles into aggregates, affects plant growth in several ways. It affects plants directly by influencing root penetration. An associated structural problem is surface crusting. Soil structure affects plant growth indirectly by determining the number, size, and continuity of pores or voids between the soil particles and aggregates. This influences the aeration of a soil which determines the balance between oxygen and carbon dioxide within the soil atmosphere. Germinating seeds and growing plants need oxygen, even at their root surfaces. If oxygen uptake by seeds or roots is restricted, seedlings and plants will not develop in a normal manner. If air transfer into and out of a soil is slowed by poor soil structure, plant respiration will be retarded and growth will slow. If root growth is restricted by poor aeration, a smaller soil volume will be occupied by roots. This will subsequently restrict the amount of nutrients and water that can be absorbed by the plants. A third way in which poor soil structure can affect plant growth is by interfering with water infiltration and redistribution or percolation. If water cannot infiltrate, it will generally runoff, frequently increasing soil loss through erosion and creating off-site problems because of sedimentation. If internal redistribution of water is restricted by poor soil structure, aeration will generally become the most limiting factor.

To select the best soil management practices, we must determine the optimum physical conditions for plant growth and identify what conditions are currently in place in the field. A soil Tilth Index has been proposed that describes the physical condition of the soil by combining numerical values for the density of the soil, the resistance of the soil to penetration, the organic matter content of the soil, the slipperiness of the soil when it is wet, and the distribution of sizes of aggregates of soil particles.

Each soil condition factor mentioned above, as well as many others, will affect plant growth, but there are also many interactions that are important. The Tilth Index combines soil physical condition indicators by multiplication after converting them to numbers between 0 and 1. The multiplication of the factors together then puts the most limiting factor as a control. A value for the bulk density factor that was near 0 would not allow the Tilth Index to be higher than itself. Several factors that have only medium values by themselves would also give a low Tilth Index when multiplied together.

Tillage is probably the most widely used method of managing soil physical conditions. Machines are available which loosen soil, invert soil, pack soil, and mix soil. Some machines can be adjusted to leave the surface of the soil flat or in ridges and furrows. Machines whose primary function is not tillage, such as planters or fertilizer applicators, can also perform limited tillage. Some tillage that has been done to change soil physical condition may in reality have been more important for its impact on the crop residue cover of the soil. Current research is showing that it may be more important to manage the residue cover than to change physical condition of the soil. However, in the more northern regions of the U. S. corn belt, maintaining crop residues on the soil surface can reduce soil temperatures and negatively affect growth and development of subsequent crops. The increased potential for harboring and transmitting plant pathogens in surface residues is another concern that is being evaluated through current research programs. [*See* TILLAGE SYSTEMS.]

In the midwestern corn belt of the United States, fall plowing has often been used to loosen and invert the soil. This practice is often followed by other tillage tools that stir and tend to pack the soil into a seedbed that is usually bare. This tillage system has often been called conventional tillage (because it was so widely used prior to 1980) and has usually resulted in the highest yields on somewhat poorly drained soil. The question has been asked whether the disturbance of the soil or the burying of the crop residue is affecting the yields. As an experimental treatment, removing the residue without disturbing the soil has been shown to have yields at least equal to removing the residue, plowing the soil, and putting the residue back on top. This would tend to indicate that the management of the residue may have been the reason for the success of the conventional system rather than the loosening and manipulation of the soil.

In contrast, some well-drained soils currently produce higher yields in field situations when the soil is not disturbed prior to planting. The important point on these soils is not always the soil disturbance, but the maintenance of residue cover that is possible without tillage. There is speculation that the effect of residue cover on soil water content and temperature is the key to understanding these situations.

An ideal management system would use the Tilth Index, a soil quality index, or some other quantitative measure of the soil condition as a benchmark for deciding whether tillage is necessary. Using this approach, the condition of the soil would be determined at any time prior to planting and tillage would be done only when benefits outweighed direct costs, such as fuel, and indirect costs such as increased soil erosion potential.

The outcome of a crop production cycle is dependant on many elements. These include weather and the condition of the soil. Soil condition can be directly manipulated by the producer but the ideal soil condition for a particular year depends on the weather that occurs between planting and harvest. A condition that promotes conservation of soil moisture might be valuable in a dry year and a problem in a year with too much precipitation. Thus, the manager must prepare for a "normal" year for the location.

As agriculture developed, farmers devised ways to use available power and technology. Originally, tillage was done with bare hands and involved only the movement of soil necessary to plant seeds and control weeds. As hand tools were developed, they were substituted for direct contact of hands with the soil but still were human muscle powered. Later, animal and mechanical power substituted for human muscle power.

Until the development of effective herbicides after 1950, there did not appear to be a choice of managing soil physical condition as a separate issue from weed control. Currently, the large majority of land used in producing agronomic crops such as corn and soybeans in North America receive applications of herbicides. Some farmers have developed ways to grow crops with few or no herbicides. These systems often depend on tillage for weed control. The use of the tillage may limit the locations where these systems may be used because of the erosion hazard posed by the loose soil and bare surface that often results from the tillage. [*See* HERBICIDES AND HERBICIDE RESISTANCE.]

Systems of crop production that use little or no tillage before planting have been developed and successfully used by commercial farmers. In these systems, it is important to know when the condition of the soil is appropriate for the crop to be produced. When proper conditions exist, plants thrive and weeds can be controlled by a combination of cultivation and herbicides. If the use of herbicides is not an option then systems without much tillage may not be feasible, even though herbicides may only be needed as a backup for weed control.

Tillage that has a short-term beneficial effect on plant growth can have long-term detrimental effects on the soil itself. Tillage often aerates the soil and speeds the breakdown of organic matter which releases nutrients for plant growth which can be good for the current year's production. This breakdown over time, however, can reduce the organic matter content of the soil which may reduce the quality or tilth of the soil.

Little evidence of long-term benefits from deep tillage has been presented in scientific literature. Special circumstances, such as a root restricting layer, may require tillage deep enough to assist with root penetration. Often, tilled soil is more susceptible to damage from compaction than untilled soil. This suggests that any tillage, and particularly deep tillage, should only be done when the benefits and long-term consequences are understood. It also suggests that prevention of damage by heavy equipment, operations performed at unfavorable soil moisture conditions, or other causes of damage is extremely important.

Heavy applications of organic material such as leaves, manure, or newspapers have been tried as ways of modifying soil physical properties such as water-holding capacity or bulk density. These applications have been tried both on the surface and in slots dug vertically in the soil. One application that seems to have worked well is the application of broiler litter (chicken manure mixed with bedding) on soils that have been leveled for flooding for rice production. The reasons for the success are not fully understood at this time, but probably relate to the nitrogen and carbon content of the litter along with any special characteristics that it may have. Attempts have been made to modify soil with chemical additives. Examples are the use of buried strips of asphalt to control water, or the use of wetting agents to try to manage movement of water in the soil. There are few, if any, chemical amendments currently in use that strictly modify the physical environment of the soil even though the use of chemicals applied primarily for plant nutrition can also modify soil physical properties.

Earthworms have been artificially introduced into agricultural fields. There is not much information that will allow an informed decision about whether such practices are of value from a cost benefit standpoint. One benefit claimed for heavy earth worm populations is better water drainage through the soil because of the channels left by the worms. Early evidence suggests that maintaining crop residue cover on the soil may be the most important factor in encouraging high populations. In the southern Piedmont, when doublecrop residues are managed so that they remain on the surface, volunteer earthworm populations increase dramatically.

At least one biological management option, choice of crops, has been shown to have an impact on soil physical condition. Crop rotations including crops such as grass or legume hays have been shown to affect the structure of the soil in a positive manner.

B. Manipulation of the Chemical or Nutrient Supplying Environment

Plants depend on the soil for most of their essential nutrients. The exceptions are carbon which is fixed from the air through photosynthesis, hydrogen which comes from the water, and oxygen. Some plants (legumes) have a close association with microorganisms that allow for the capture of nitrogen from the air usually at the cost of the plants feeding the microorganisms. Two elements, carbon and nitrogen, have extensive cycles that include the soil, plants, and animals. They form the basis for many food chains that connect such widely varied life forms as bacteria, plants, rabbits, birds of prey and humans. [*See* Nitrogen Cycling.]

The natural physical, chemical, and biological soil conditions or those created through various soil and crop management practices generally determine how efficient a soil will be in supplying nutrients to plants. Cold soil may slow plant growth and root development and make it difficult for plants to take in water or other nutrients. Soil that is too acid or too alkaline may cause nutrients to be either present in toxic concentrations (such as for aluminum or manganese) or unavailable (such as for phosphorus and zinc) to plants. [*See* Soil, Acid.]

The pH of the soil is very important in determining soil productivity. Some plants, such as alfalfa (*Medicago sativa L.*), perform at an optimum level when soil is almost neutral (i.e. has a pH near 7). Other plants such as blueberries (*Vaccinium* spp) grow much better when pH levels are below 5. Soil pH can be adjusted either up or down with the addition of appropriate materials such as lime or sulfur. An example of a problem created by a high pH (above 7) is iron deficiency or chlorosis in soybean. In the midwest on high pH soils, some soybean varieties have difficulty getting sufficient iron for photosynthesis. Similar problems have been reported for grain sorghum in the southern plains area of the United States. The problem can be solved by reducing the pH (although this is expensive in that area), spraying the plants with special iron-containing compounds, or using a variety that is not as susceptible to the problem. Selection of a tolerant variety is the most common and least expensive choice and is an example of soil and crop management based on plant selection or biology. Soils that are too acid may cause soybean to suffer from a lack of nitrogen if the rhizobium bacteria that normally fix nitrogen for the plants cannot function well.

Organic amendments, such as crop residue, manure, sludge, and yard waste, can be applied to the soil as a source of carbon which becomes incorporated into the soil organic matter pool and nutrients which become available for uptake by subsequent generations of plants. The exclusive use of such materials as the sole source of nutrients leads to the term organic farming, and if all materials on the farm are continually recycled the practice can be considered a closed system. However, if grain or other plant products are sold from the farm, supplemental amounts of various nutrients,including carbon, may have to be supplied by off-farm inputs (i.e., fertilizer) to replace nutrients contained in the material that is sold. On the other hand, when the primary products sold are produced by animals such as meat, wool, eggs, or milk, the manure from the animals contains much of the original nutrients of the crops that were used to feed the animals. This means that the majority of the nutrients remain on the farm and can be recycled by applying the manure to the crop land.

When specialized farms raise only livestock, there may be a problem with manure. Creative means must be found to allow the manure to be effectively used for the benefit of the soil without becoming an environmental hazard. If this does not happen, limited land area may lead to a problem of manure disposal rather than productive manure use. Current research has shown that some of the highest late-spring soil nitrate nitrogen concentrations are found in fields that have received manure. Preventing an accumulation of phosphorus in soils receiving manure is another challenge facing those who are developing manure management guidelines. This is most difficult if manure is being applied at rates that are sufficient to ensure adequate nitrogen for growing continuous corn.

Developing environmentally acceptable strategies for manure management on specialized livestock farms is not hopeless, since in Iowa, one chicken egg production operation has developed a way to produce fairly dry manure that can be handled, sold to, and managed by local farmers in the same manner as an inorganic, commercial fertilizer material.

The use of cover crops is of relatively recent origin, when compared to green-manuring practices that were utilized by the Greeks more than 300 years B. C. The function of cover crops is to protect the soil in various ways. They prevent soil erosion while growing by protecting the soil from the impact of raindrops and by slowing runoff. When incorporated, cover crops add organic matter to the soil, increase permeability, and thus increase infiltration, slow runoff, and decrease erosion. Cover crops can reduce leaching of nitrogen, potassium, and possibly other nutrients, especially on sandy-textured soils. On fine-textured soils, cover crops have been shown to improve physical properties of aggregation, porosity, bulk density, and permeability. By providing a readily available carbon (food) source, cover crops can cause an increase in microbial activity which subsequently increases aggregation.

Farmer interest in and research emphasis on incorporating cover crops into production systems decreased dramatically during the 1960s. This probably occurred because manufactured fertilizer nitrogen could be substituted for green manure and cover crop additions that supplied essential plant nutrients. Also, herbicide technology developed rapidly during that period, making it very easy to control perennial and annual weed species.

Interest in cover crops for soil erosion control, especially following soybean, was renewed with findings that soil loss from a Grundy silt loam (Midwestern United States) was 35% greater for corn following soybean than for either soybean after corn or a continuous corn rotation. The increased soil erosion following soybean has been attributed to lower dry matter production, less residue cover, and the soil-loosening action of soybean roots. Growing cover crops on Mexico silt loam soils in Missouri improved water quality by reducing nitrate, ammonium, and phosphorus losses when compared to no-till soybean grown without a cover crop. The negative aspect of cover crops was that they decreased soybean yields from 29 to 79%. This was probably due to the use of soil water by the cover crops that was no longer available for the soybean crop.

Cover crops provide an effective method for improving water quality because they accumulate and retain plant nutrients as well as reduce soil erosion. The effectiveness of cover crops with regard to protection of the soil by canopy depends upon (a) density of stand, (b) soil coverage, (c) total amount of cover, (d) average height, (e) rate and period of growth, (f) spacing of plants, and (g) method of harvest, which now would be more accurately termed "method of management." For nutrient and/or biocycling of plant nutrients, these same aerial characteristics, plus the extent and vigor with which the cover crop root systems explore the soil, are also important. If legumes are used as cover crops, they can provide nitrogen through fixation for subsequent grain crops.

In Kentucky, growing hairy vetch as a winter cover crop for 10 years resulted in an additional 20 kg/ha of nitrogen uptake by a subsequent corn crop and resulted in higher grain yields. For more northern locations, however, it has been reported that a major conservation tillage research need for the Midwest is the development of cropping strategies and management schemes that make cover crops more compatible with common crop rotations.

Cooperative research efforts between USDA-ARS scientists and farmers have resulted in on-farm cover crop evaluations during the 1990s. Initial results of those investigations have shown that one reason cover crops are not used more extensively in ridge-tillage systems is that they can lead to nitrogen deficiencies in subsequent corn crops. This apparently occurred because of lower net mineralization of soil organic matter or greater denitrification losses before planting. Additional studies are being conducted to determine the amount of nitrogen temporarily lost because of microbial immobilization.

One of the most difficult challenges for incorporating cover crops into current crop rotations in the Midwest is stand establishment. During the 1950s and 1960s when interseeding and forage establishment were more prevalent, practices using tools such as a cultipacker seeder were developed to interseed directly into a corn crop. Those systems were developed, however, when plant populations for corn were much lower and when standard row width was at least 1 m instead of current widths of 0.75 m or less. The combined effects of higher plant density and narrower rows have contributed to higher corn grain yields with current practices, but with nearly total light interception, it is futile to plant a cover crop until the crop is nearly mature. For much of the Midwest, this results in minimal growing time for establishing cover crops using current germplasm resources.

On-farm research trials in the northern corn belt have shown that for success in much of this region, cover crops should be overseeded when soybean leaves begin to senesce (turn yellow), but before they drop from the plant. A study in Missouri attempted to establish annual or perennial cover crops and subsequently grow no-till soybean after killing 60-cm strips around each row and suppressing cover crop growth between rows with various herbicide combinations. The preliminary observations from this study indicate that competition for water by the cover crop and other weeds may be difficult to overcome.

Winter rye and Italian ryegrass have both been shown to be very effective cover crops for reducing leaching losses of residual nitrogen. A disadvantage of winter rye is that it can be very aggressive during the following spring and deplete available soil water supplies and thus stress the primary crop. This has been reported for sandy soils in the southeastern United States and observed in on-farm experimentation in Iowa. Currently, the use of spring oats seeded in autumn is being evaluated as a cover crop for Iowa. The oats grow rapidly during autumn and provide cover for the soil, but freeze and die in winter and therefore do not deplete soil water reserves in spring.

Oats also provide an excellent companion crop for hairy vetch when broadcast into scenescing soybean.

Commercial fertilizer is commonly used to supply nitrogen, phosphorus, and potassium to crops. The amount of fertilizer elements required by crops should be determined by taking samples of the soil and having them analyzed by commercial or university laboratories. Fertilizer recommendations are usually based on research that relates the level of nutrient measured in the soil, the amount required for best plant growth, and the amount of nutrient required to change the soil status from measured to desired levels. It is possible for the manager to test the soil for nutrients with a kit but it is not a common practice. [*See* FERTILIZER MANAGEMENT AND TECHNOLOGY; SOIL TESTING.]

There is considerable interest in a concept called precision farming or location specific farming along with some other names. The idea is to apply materials including fertilizer and herbicides differentially to specific locations on the field by need rather than at a single rate to an entire field based on average requirements. Measurements on fields that have been uniformly treated in the midwest have shown crop yields varying as much as fourfold from location to location within the field. This indicates a possible opportunity to be more efficient in the use of fertilizers or other inputs.

Farmers who wish to implement this differential management strategy will need equipment that includes computers and other equipment to calculate the position of the equipment within a field and then apply materials according to a prescription. Some farmers have implemented this type of precision without computers but it appears that they might be able to make more complete use of the technology with computers and automated location finding equipment. Computers will probably be required to handle the large amount of data on material applied and resultant crop yield so that this management of small areas can be successful. The economics of this type of practice remain to be worked out.

There is the perception that location-specific application depends on commercially produced materials. It is true that these materials are formulated to allow precise mechanical application and are well suited to this technology. However, with good management and innovation such as that noted in the Iowa chicken manure example, precision application should apply to manure and other biological residues as well.

If this technology is applied properly, there should be environmental benefits as well as economic returns to the farmers. A material that is not applied cannot leave the soil system to become a pollutant. It is also true that materials that are not produced by industry do not leave other waste products behind at the site of manufacture.

C. Manipulation of the Biological Environment

The soil is a holistic life system that is very dynamic. This life ranges from single-celled organisms to complex life forms such as animals and higher plants. A single gram of soil contains billions of microorganisms that may represent in excess of 5000 distinct species. The community that is the soil depends on the life that is within it for many of the cycles that make plant growth possible. When plants and animals die they are decomposed and their components recycled by bacteria, fungi, actinomycetes, yeasts, etc. Some of the soil microbes can cause disease or other problems for plants or animals. This is a risk to life, but without the general biological community in the soil, life as currently known would not be possible. [*See* SOIL MICROBIOLOGY.]

There is much interaction between higher plants and simple organisms. An example is the cooperation that legumes and bacteria use to mutual benefit. The benefit to the plant is a supply of nitrogen in a form that can be used by the plant. Several groups of fungi also form close associations with plant roots and have been shown to improve nutrient and water uptake. These associations are mutually beneficial, with the fungi receiving carbon substrates from the plant. These fungi infect the root cells and extend out into the soil, effectively increasing the soil volume which is explored by the plant rooting system. Nutrients such as phosphorus, nitrogen, zinc, copper, and sulfur can then be absorbed by the fungi and translocated to the plant. It has been observed that the beneficial effect of this association is most pronounced with plant species that do not develop extensive fine rooting systems, such as grasses.

The biological component of the soil can be manipulated by the addition of life forms such as earthworms. Because the inoculated organisms must compete with the indigenous populations for available nutrients, direct inoculation of soil with bacteria or fungi is often not an effective practice. A more effective strategy has been to use direct seed, or root system inoculation. Rhizobia, the nitrogen fixing bacteria that form symbiotic relationships with soybeans and other legumes, is often directly applied to the seed. This is necessary because the host–Rhizobium relationship is a very specific one, dependant upon the species of both plant and the microorganism. Direct inoculation of the rooting systems of nursery plants with specific fungi is also a common practice.

When a new legume crop is introduced to an area, it has been common practice to identify and provide the appropriate bacteria on the seed so that they can work with the plant roots to provide nitrogen. This is called inoculating the seed and was done as the soybean crop was introduced to the United States from Asia. Without inoculation, the crop might grow but not be as productive as it possibly could be.

Introduction of plants and soil microbes has had unforeseen effects, particularly when the distance between source and introduction site is long. For example, the introduction of some plants from one country to another led to their becoming serious weed problems. Johnson Grass [*Sorghum halopense* (L.) Pers.] is a current weed in the southern United States that was introduced as a potential crop for that area with another example being Kudzu [*Pueraria lobata* (willd.) Ohwi].

Often these manipulations of the biological component are accomplished by changing other management practices. For example, increased use of conservation and reduced tillage, and greater awareness of alternative farming systems have resulted in numerous questions regarding the impact of soil fauna on soil quality. This occurs because tillage interactions alter soil and crop residue conditions. As tillage decreases, crop residue decomposition rates decrease and microenvironments that are favorable for soil fauna are created. Comparisons between no-tillage and conventional tillage have shown that as tillage decreases, populations of ground beetles, spiders, and earthworms increase.

Earthworm activity has been shown to reduce surface crusting, hasten decomposition of crop residue mats, and alter the susceptibility of soils to water erosion. Quality and location of residues influence earthworm growth, amounts of ingested soil, number of burrows, and openings to the surface. One negative aspect of earthworm activity is that continuous burrows (macropores) can affect solute transport and increase the potential for rapid movement of surface-applied agricultural chemicals through the soil profile.

Surveys of earthworm species in different agricultural crop management systems in the Midwest are limited. In Indiana, *Lumbricus rubellus* (Hoffmeister), *Aporrectodia turgida* (Eisen), *Octolasium lacteum* (Savigny), *Eisenia rosea* (Savigny), and *L. terrestris* (L.) are reported in reduced tillage systems in corn (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr). In Minnesota soils, *L. rubellus* and *A. tuberculata* were the species most often found in fields planted to corn. Recent investigations in Iowa showed that as the amount of tillage increased, earthworm numbers generally decreased. They found the largest number of earthworms where alternate farming practices have been used for more than 20 years. The predominant species was *A. tuberculata*. They also reported that regardless of management practice, the highest number of worms were found in Canisteo soil on the toeslope landscape position. These evaluations show that earthworm populations can be influenced by farming practices throughout the U. S. corn belt region.

Managing the chemical or physical status of the soil can affect the biological environment. Changing the soil pH, a common practice, can dramatically affect both type and quantity of microbial species present. An example is the control of potato scab by keeping the soil pH below 5.2. From the physical condition standpoint, it has been shown that severe tillage of an area can lead to a reduction in earthworm population and may even increase the population of microorganisms that degrade organic matter.

D. Sources of Information

There are a number of organizations or people that can help with questions on soil management. The local extension office in most counties of the United States can answer questions directly or help with contacts at the state agricultural college. The state agricultural college and state department involved with agriculture or natural resources are possible sources of information. The Soil Conservation Service (SCS) which is a part of the U.S. Department of Agriculture (USDA) maintains local offices in most parts of the United States and can help with questions on soil conservation. The USDA also has the Agricultural Research Service that can be contacted directly or through extension or the SCS. There are also national or local private organizations such as the Conservation Tillage Information Center (CTIC) based in West Lafayette, Indiana, or the Rodale Institute that work nationwide or the more local Practical Farmers of Iowa that can answer questions or provide information to assist land or soil managers.

The American Society of Agricultural Engineers (St. Joseph, MI), American Society of Agronomy (Madison, WI), and the Soil and Water Conservation Society (Ankeny, IA) are examples of professional organizations that have printed information available on soil management and can provide names of professionals working in the area.

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Soil Microbiology

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Glossary

Aerobe Organism using O_2 as its terminal electron acceptor in its metabolic pathways
Anaerobe Organism using an organic compound more reduced than CO_2 as its terminal electron acceptor in its metabolic pathways
Autotroph Organism which does not require any organic carbon for its energy source or for its growth
Denitrification Biological reduction of the N oxides to a more reduced N oxide or N_2
Facultative anaerobe Organism using O_2 as its terminal electron acceptor, but in its absence uses some oxidized compound, such as NO_3^- or $SO_4^=$
Heterotroph Organism requiring organic nutrients
Nitrification Biological oxidation of NH_4^+ to the products of NO_2^- or NO_3^-
Substrate Compound used for a source of nutrients or for energy for growth or maintenance of microorganism viability

Soil microbiology is that branch of soil science dealing with the microorganisms found the soil and their relationship to soil management, agricultural production, and environment quality. The soil microbiologist not only studies the numbers and kinds of microorganisms found in soil, but is also interested in the effect of microorganisms on nutrient cycling, biocontrol of pests, bioremediation of polluted sites, and survival of introduced microorganisms in the soil, especially as these functions affect crop production, environmental quality, and the restoration of stressed environments.

I. Soil as a Medium for Microbial Growth

The soil is a unique environment for the growth of microorganisms, unlike that microorganisms encounter in traditional culture tubes found in most microbiology laboratories. For this reason it is important to assess the effect of some of the soil physical and chemical properties on the growth and function of microbes. In the natural state, the soil environment is a heterogeneous medium of solid, liquid, and gaseous phases. In an average soil the proportion of solid:free space is about equally distributed. The free space is occupied by either liquid or gas. However as the liquid phase of the soil increases the gaseous phase decreases. For typical conditions the proportions can be thought of as 50:25:25 for solid, liquid, and gas phases, respectively. [*See* Soil Chemistry.]

The solid phase of the soil is composed of organic or inorganic components, ranging in size from 2000 μm to <2 μm. The larger inorganic fractions are either sands or silts and the smallest size fraction is the colloids or clays. The proportion of the individual solid components in a soil imparts many important characteristics to the soil, ultimately affecting the numbers or activities of the organisms. Generally soils with a higher proportion of sand and silt tend to retain less water and are described as well-drained. Soil with a more even distribution of separates or greater proportion of clay has the potential to be less well-drained, often experiencing an abundance of water and the associated characteristic of being less well-aerated. [*See* Soil Genesis, Morphology, and Classification.]

The colloidal fraction of the soil has a large and negatively charged surface where nutrients can be retained within the soil. The negatively charged surfaces provide exchange sites for the cationic nutrients. Depending on the charge density, cations adsorbed on the surface of colloids may be difficult to remove by microorganisms. Compared to a conventional culture tube, where the organism is growing in a three-dimensional matrix, in the soil, the organism is essentially growing in a two-dimensional matrix, with respect to the colloid surface. This is true because at most biologically active moisture contents the thickness of the moisture films on the colloids is similar or even smaller than many microorganisms (Table I). In addition to affecting the availability of nutrients, the charge associated with the solid surfaces influences surface potential and diffusion of nutrients to, or diffusion of metabolic products away from, the microorganism. Likewise this charge may affect surface acidity, which in turn affects the availability of nutrients or alters the activity of various extracellular enzymes, either enhancing or inhibiting critical enzyme reactions needed for growth or survival of microorganisms in the soil.

The adsorption of water to charged surfaces alters the structure of the water and affects its availability to microorganisms. Water relations within the soil environment need to be understood in terms of the total soil water potential, which is composed primarily of matrix, osmotic, and other potentials, including a gravitational factor which is most often negligible. The matrix component of the total soil water potential is related to the attraction of the solid surface for water and to surface tension. As the soil becomes drier the amount of energy required to utilize the water increases. The osmotic potential is related to the concentration of the dissolved solutes. Under most soil conditions the contribution of the osmotic potential to total soil water potential is small, except under very dry soil conditions or in environments where evaporative losses are high, and solutes have been concentrated in the soil solution. As total soil water potential becomes low it is more difficult for the organisms to extract water for growth and to maintain membranes intact. [*See* Soil–Water Relationships.]

TABLE I
Relative Sizes of Soil Components

Components	Size (μm)
Sand	2000–50
Silt	50–2
Root hairs/fine roots	±75
Clay	<2
Bacteria, diameter	0.2–2
Fungi, diameter	0.5–3
Pore diameters filled	
0.03 MPa (FC)[a]	5
1.5 MPa (WP)[b]	0.1
Moisture films	
0.05 MPa	<0.1
0.10 MPa	<0.03

[a] Field capacity.
[b] Wilting point.

The gaseous phase of the soil occupies approximately one-half of the free space. All of the atmospheric gases can be found in this space. Oxygen in the soil is somewhat lower than in the atmosphere whereas CO_2 is somewhat higher. These differences are attributable to utilization of O_2 by soil microorganisms and the normal production of CO_2 during various metabolic functions. While total pore (free) space might be equal for two different soils, the two soils might have two distinctive growth patterns for microorganisms. If all of the pores are small, gas exchange and water movement might be severely restricted with the soil tending to become anaerobic. On the other hand if the pores are all of a large size, aeration status might be satisfactory, but the soil might have poor water relations since infiltration and percolation of water might be excessive. Ideally the soil should possess both large and small pores, for optimum moisture and aeration conditions for the microbes.

The last feature distinguishing the soil as medium for microorganisms compared to other cultural conditions is that competition exists among a variety of different organisms for moisture and nutrients. Much of this competition is among microorganisms, such as fungi, bacteria, actinomycetes, but significant competition exists with other forms such as soil animals and plant roots. Figure 1 brings all of the components of the soil together and demonstrates the complex nature of the soil environment for microorganisms. This scheme shows the clays with the adsorbed cations or microorganisms; the soil solution with suspended cations, anions, and microorganisms; and finally the plant roots in the remaining spaces, competing with the microorganisms for nutrients. Understanding how the microorganism grows must be in the context of soil physical, chemical, and biological properties and how they interact.

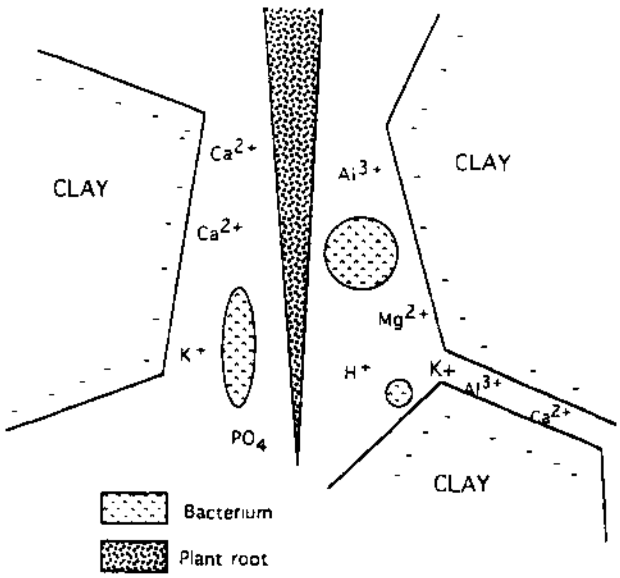

FIGURE 1 Different components of the soil system, including the clays, cations, anions, microbes, and plant roots. Note the negative charge at the surface of the clays. The areas between the clays are the free spaces and are occupied by water or gases. If the moisture film is thick enough the organisms may be free in the soil solution, otherwise the organisms will be intimately associated with the clay surfaces.

II. Microorganisms in Soil

A. Kinds and Distribution

A variety of different size organisms reside in the soil ranging from bacteria to plant roots as well as the suborganismal units referred to as viruses (Table II). The bacteria are most abundant often ranging to an excess of 10^8 g^{-1} soil and represent as many as 10^4 different species. The organisms function in a variety of ways, producing various antibiotics, mineralizing organic compounds to inorganic nutrients, oxidizing reduced forms of nutrients, i.e., $S° \rightarrow SO_4^=$, reducing oxidized forms of nutrients, i.e., $NO_3^- \rightarrow N_2$, reducing N_2 to an organism utilizable form(NH_3), and degrading organic matter or various petrochemicals. Other organisms are important plant, animal, or insect pathogens.

Organisms are for the most part more numerous near the soil surface than at deeper depths (Table III). There are many reason why this is true. Normally the soil near the surface has better physical properties, i.e., it is better aerated and moisture relations for the organisms tend to be more favorable. Also the soil is warmer and is more richly supplied with O_2 than the subsoil. The surface soil also has a higher organic matter content, thus providing more carbon for growth of new cells and energy to sustain growth and survival of organisms than at deeper depths in the soil.

It is interesting that anaerobic organisms also exist near the soil surface in an environment normally thought of as being aerobic. This can be explained in the following manner: Soils have structure, in that individual soil particles are united together in more or less stable aggregates. Due to slow diffusion processes the interiors of aggregates can be anaerobic while their surfaces are aerobic. Also as aggregates come together, small pores may result, thus giving rise to a water-saturated environment with a corresponding lack of O_2.

TABLE II

Kinds and Sizes of Microorganisms or Viruses Found in Soil

Organism or virus	Dimensions (μm)
Tobacco mosaic	0.3 × 0.02
T_2-Bacteriophage	0.2 × 0.06
Micrococcus spp.	1.0 (diam)
Pseudomonas aeruginosa	1.5 × 0.5
Serratia marcescens	1.7 × 1.0
Bacillus polymyxa	0.6–0.8 × 2.0–5.0
Bradyrhizobium japonicum	0.5–0.9 × 1.2–3.0
Nitrosomonas europaea	0.8–0.9 × 1.0–2.0
Streptomyces spp.	0.5–2.0 (diam)
Mucor hiemalis	8.0 (diam)
Euglena gracilis	50 × 15
Nostoc spp.	5 × 13
Neurospora crassa	5.7–11.7 (diam)

B. Growth and Survival

The growth of soil microorganisms is governed by the interactions imposed by the soil as a whole, e.g., soil physical properties such as porosity, bulk density, texture, water content, and aggregation in concert with certain soil chemical properties such as surface charge, nutrient content, acidity, mineralogy, and organic matter. Each property or interaction among properties will impinge on the final outcome of growth and survival. However, from the standpoint of the microorganism, what essentials are needed to sustain growth or survival? Specifically microorganisms needs carbon, a source of energy (electron donor), and a terminal electron acceptor, provided nutrients, water, etc. are in adequate supply (Fig. 2). For some organisms the soil organic matter can supply

TABLE III
Distribution of Various Kinds of Microorganisms as a Function of Soil Depth

Depth (cm)	Horizon	Aerobic bacteria	Actino's	Bacteria spores	Anaerobic bacteria
		No./g soil			
3–8	A1	1291×10^3	191×10^3	1097×10^3	156×10^3
20–25	A2	1424×10^3	177×10^3	554×10^3	101×10^3
35–40	A2B1	276×10^3	123×10^3	115×10^3	36×10^3
65–75	B2	61×10^3	16×1^3	16×10^3	7×10^3

Adapted from Starc, A. (1942). *Arch. Mikrobiol.* **12,** 329.

both the carbon and the energy needed for growth in the form of carbon compounds more reduced than CO_2. These organisms constitute by far the greatest number and diversity of the organisms in the soil. Known as heterotrophs, these microorganisms contribute to a wide range of activities within the soil. Other soil microorganisms obtain carbon for growth from CO_2 or CO_3 in the soil solution. These organisms are known as autotrophes and depending on how they obtain their energy are either phototrophes (energy from light sources), represented by many algae and green plants or chemotrophes (energy from the oxidation of inorganic compounds), for example, NH_4^+ to NO_2^- or NO_2 to NO_3^-.

Regardless of the type of microorganisms found in the soil, all are governed by several "laws." The first law, Liebig's Law of the Minimum, suggests that the growth (increasing numbers, activity, survival, biomass, etc.) of an organism is regulated by the factor which is in lowest supply in relation to what is needed. This law refers to the external or environmental factors regulating microorganisms. On the other hand Shelford's Law of Tolerance suggests that successful growth depends on the needed growth factors remaining within the tolerance range of the organism. Thus this law deals with the biology of the organism itself in relation to growth or activity. Finally Odum's Combined Law suggests that total growth depends on the successful interaction between the limiting factors (Liebig's Law) and the biological tolerances of the organism itself (Shelford's Law).

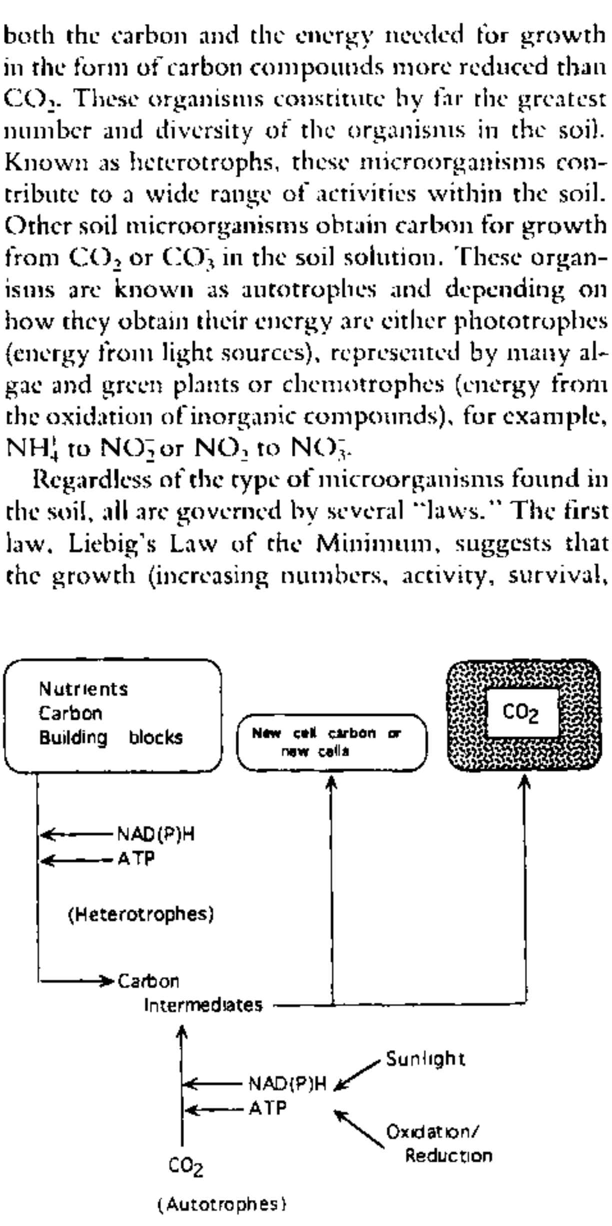

FIGURE 2 Simple model for the growth of microbes.

The energy requirement for the cell is not just for growth. Energy needs may be apportioned to motility, accumulating substrates or nutrients across a membrane, hydrolyses and resynthesis of macromolecules, and maintenance of membrane potentials. These additional needs, apart from growth can be lumped under the general category of maintenance energy. Although energy is frequently limiting for growth, the microorganisms must have enough energy to maintain the integrity of the cell, otherwise it cannot survive and death occurs.

C. Measuring Numbers/Activities

Microorganisms in soils are never static in numbers or activity; therefore, the representation of some number or activity is a property of a particular time, when the soil was sampled. Recognizing that microorganisms are in a dynamic equilibrium and due to the highly complex nature of the soil medium itself, attempts to study microorganisms will be difficult and often laborious. Therefore it is essential that each attempt to characterize some microbial property be firmly supported in advance by a specific set of study objectives.

There are two ways in which to enumerate microorganisms in the soil, one is a direct count and the other an indirect count, using selective media. Both approaches rely on diluting the sample so organisms are in a range which can reliably be counted. In the former technique, an appropriate dilution is selected and the organisms are mounted on a glass slide. Subsequently the preparation is viewed directly using conventional microscopy and the microorganisms are counted or the organisms are stained with an suitable dye prior to counting. When the dye selected is a fluorescent dye, viewing must be done using an epifluorescent microscope.

For indirect procedures, aliquots from suitable dilutions are placed on a selective medium, the medium is incubated, and counts are made of the colonies formed. By varying the medium used, different groups of organisms can be counted. Media can be made selective using different energy sources (e.g., starch or cellulose), adding selective antibiotics (e.g., chloroamphenicol) which inhibit specific groups of microorganisms, moderating the acidity of the solution or combining a specific energy source with an antibiotic, etc. Counts obtained by plating are always less than those obtained when using direct methods (Table IV). There are several reasons why this may be true. Direct counting methods do not normally distinguish between living and dead organisms, where only those cells capable of growing on the medium used would be counted when cultural methods are used. The indirect methods may further underestimate the population because of selective pressures among the community of microorganisms which might prevent a group of organisms from growing on the medium. Further one must deal with the issue of viable, but nonculturable organisms. Not all microorganisms are culturable on currently available media. Thus some microorganisms may be present which are viable, but which cannot be enumerated directly.

Other ways of studying microorganisms in the soil emphasize some important function or property of microorgansims. These methodologies are varied and in the space available cannot be discussed individually. However several techniques are worth mentioning. For the determination of microbial biomass soil samples containing microorganisms are treated so the microbial cells are lysed and the microbial C or N is extracted, measured, and compared to the C or N in paired samples in which the cells were not lysed.

Since CO_2 is respired during growth or cell maintenance, a measure of the activity in a soil sample can be made by determining the amount of CO_2 evolved during a specified period of time. Using ^{14}C-labeled substrates, one could measure $^{14}CO_2$ and determine what portion of the substrate has been degraded. While this doesn't give an estimate of the population size, it does give an indication of the activity of the existing population.

Another way to study activities of organisms is to measure the appearance of product or disappearance of substrate. For instance, if one was interested in the oxidation of reduced nitrogen compounds ($NH_4^+ \rightarrow NO_2^- \rightarrow NO_3^-$), NH_4^+ disappearance could be followed over time or the rate at which NO_2^- or NO_3^- appears could be used to give an indication of the nitrification potential of the soil. Any reaction for which a measurable substrate or product can be assayed can be followed in this fashion. This is also the underlying principle for the determination of many of the extracellular enzyme activities in soil. In some cases, the measurements involve the use of analogous substrates and their subsequent enzymatic products. For instance consider the enzyme alkaline phosphatase. The substrate added to the reaction mixture is *p*-nitrophenol-PO_4, not normally found in soils.

TABLE IV

Comparison of the Numbers of Microorganisms Found in Soil[a] Based on the Method of Determination

Soil	Direct microscopic count	Selective media (solid)	Selective media (liquid)
		No./g soil	
Spodosol	500×10^6	7.5×10^6	500×10^6
Mollisol	9000×10^6	25.0×10^6	7000×10^6
"Garden soil"	7000×10^6	16.0×10^6	6000×10^6

[a] In the plow layer under perennial grasses [adapted from Krasil'nikov (1958). Soil microorganisms and Higher Plants. Academy of Sciences, USSR].

However, after incubation and in the presence of a phosphatase enzyme, the othro-PO_4group is cleaved from the parent compound, leaving *p*-nitrophenol. Under the appropriate conditions *p*-nitrophenol is colored and the intensity of the color can be used to indirectly quantify the amount of phosphatase enzyme present in the original sample. [*See* SOIL TESTING FOR PLANT GROWTH AND SOIL FERTILITY.]

III. Soil Organic Matter

A. Unifying Feature in Soil Science

The element carbon (C) is interesting for many reasons. It occurs in a variety of forms from CO_2 to CO_3^-, to reduced compounds such as carbohydrates, and to graphite or diamond. The large variety of C compounds is attributable to the atomic structure of C which permits a variety of bond types. However the soil microbiologist is primarily interested in CO_2 resulting from the metabolic activity of heterotrophic organisms or the more reduced forms which occur as part of organic residues or soil organic matter. The latter is known by a variety of names, many of which are interchangeable. The best known names are probably soil organic matter (SOM) or humus.

The SOM can be considered one of the unifying principles of soil science (Fig. 3). All aspects of soil science interact in some way with the SOM, whether it be biology, chemistry, or physics. From a biological viewpoint, SOM can be considered a source of nutrients for organisms and contributes to the overall negative charge found in soils. Likewise SOM plays an important role in the complexing of Al in acid soil, as well as serving as a source of energy (electron donor) for the heterotrophic organisms. From a purely physical standpoint, SOM contributes to the stabilization of soil aggregates, which in turn contributes to a better water-holding capacity and aeration or provides a better means for percolation of water.

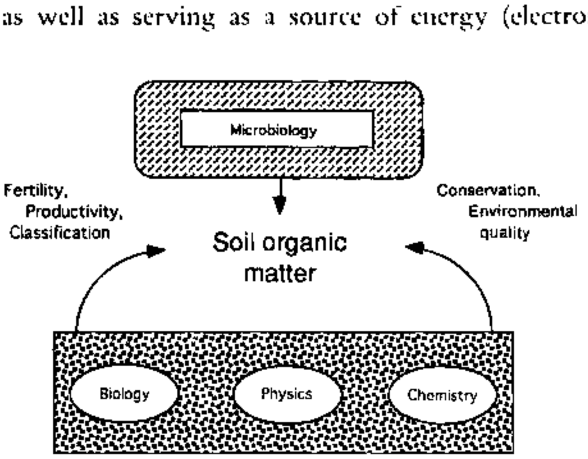

FIGURE 3 Soil organic matter as a unifying principle in soil science, affecting fertility, productivity, classification, conservation, and environmental quality.

B. Composition/Formation

The SOM is composed of a variety of compounds of recognizable chemical structures such as sugars, proteins, lignins, and amino acids to others of less precise structure such as humic acid, fulvic acid, and humins. Although a structure has been proposed for the latter group of compounds, it varies depending on soil parent material, vegetation type, and human activity. These fractions of the SOM have components similar in structure to lignins and polyphenols, as well as a variety of functional groups including OH , COOH , and OCH_3^-. This fraction also contained N in heterocyclic configurations as well as NH and amino acids bonded at various points.

Often SOM has been studied and classified using different fractionation procedures (Fig. 4). However considering functional pools, a unified picture emerges, ultimately which may bring together a lot of the theories about SOM. The functional pool approach looks at SOM as microbially active pools. As an additional benefit the functional pools may give an idea of the residence time of different fractions.

Different mechanisms for the formation of SOM have been proposed; however, almost all have certain similarities. Figure 5 brings together common components of many decomposition and formation schemes for SOM. Most models of decomposition depend on size reduction of organic remains via microbes, animals, and physical forces. Subsequently each model requires the breakdown of the organic remains into its constituent components, i. e., chitin, lignin, cellulose, etc. The components are then utilized by microorganisms as a primary energy source with the liberation of CO_2 and the production of microbial tissue. Some of the components may be used for skeletal structures via condensation or polymerization with the formation of a larger molecule (humic substances). The rate at which these reactions occur depends on all of the environmental factors and the nature of the organic remains. Regardless of the mode of formation, more stabilized products are formed.

C. Management Implications

The rate of turnover of organic materials is governed in part by environmental factors and management

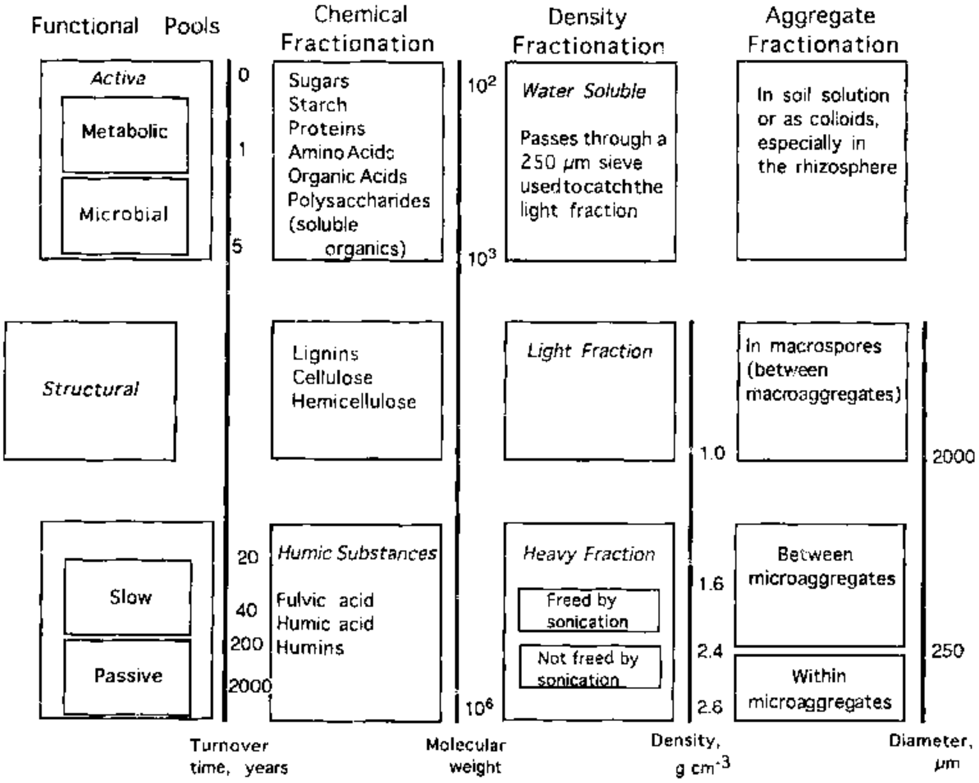

FIGURE 4 Different fractionation schemes used to characterize soil organic matter and their relationship to functional pools as components of soil organic matter.

techniques. Obviously increasing or widely fluctuation temperatures enhance the turnover of SOM. Alternating wetting and drying also contributes to an enhanced rate of turnover. However, it is also known that cultivation may contribute to the degradation of the organic fraction on the soil, but at the same time may provide an important mixing feature. Different cropping systems through rotations, grazing, or no-tillage can influence the SOM. Regardless of the management scheme in place, those practices which enhance the quantity of the SOM fraction, such as rotations, appropriate residue management, and minimum tillage are usually to be favored. Excessive cultivation, monocultures, removal of residues, etc. are among the management practices that should be avoided if SOM management is to be optimized.

IV. Nutrient Cycling

A. Mineralization/Immobilization

Mineralization can be thought of as the biotic reactions resulting in the transformation of the soil organic matter from organic constituents to the formation of inorganic products(C, N, S, P, etc.). The microorganisms are decreasing the biochemical complexity of a component of the ecosystem. For example, during mineralization a protein can go to NH_4^+, CO_2, and $S^{=}$. The converse of the mineralization reaction occurs during immobilization, where inorganic nutrients are assimilated and converted into organic forms. Following the analogy previously used, the biochemical complexity of the ecosystem is increasing. Since mineralization and immobilization are going on simultaneously, it is the net effect which is observed. If mineralization is greater than immobilization, then the inorganic products will build up. On the other hand if immobilization is greater than mineralization, it will appear that inorganic products are disappearing.

The combined processes of mineralization and immobilization occur as a consequence of growth of the microorganisms, when some utilizable substrate is present in the soil. Assume that an organic substrate in the form of an animal waste product is added to the soil. This product in its simplest form contains a variety of C-based compounds, including proteins. The organisms present in the soil respond to the input

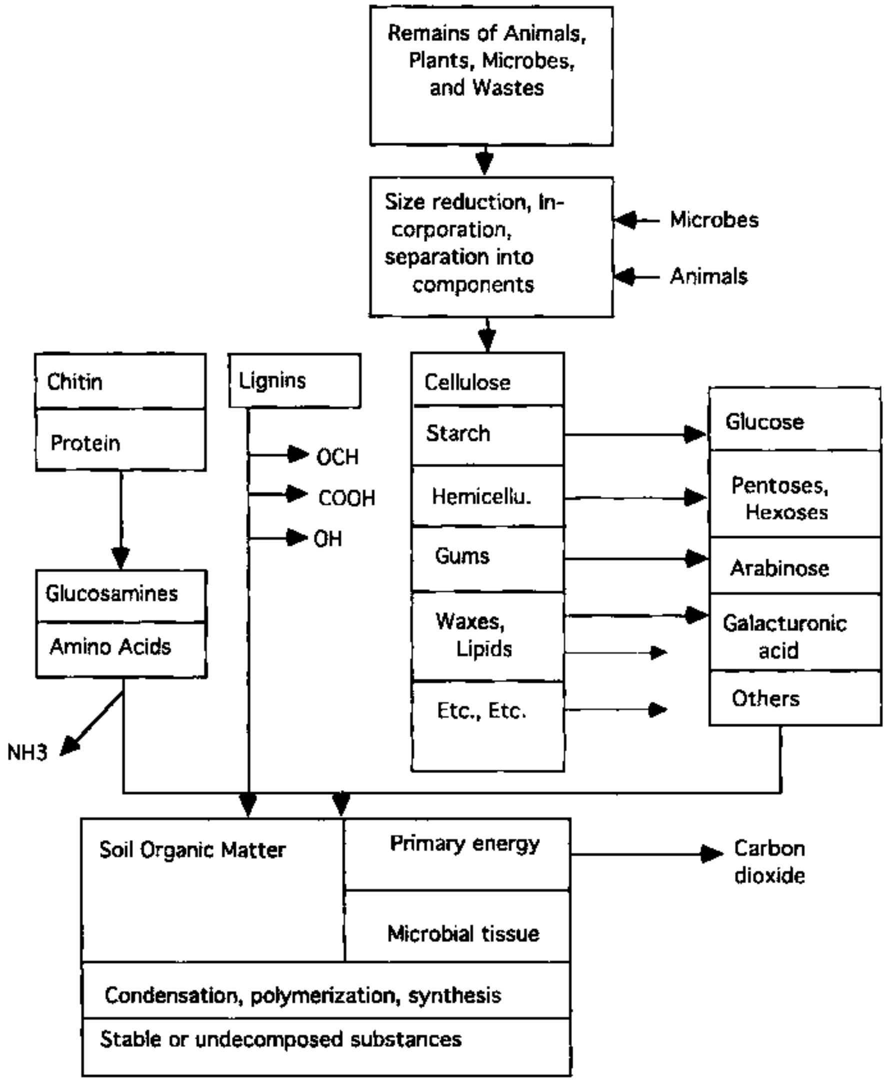

FIGURE 5 Simple model for decomposition of organic residues and formation of the soil organic matter.

of C and energy, by using the material to increase their number. Besides an increase in the total microbial biomass (incorporation of C from the substrate), a corresponding increase in CO_2 is observed and a variety of extracellular enzymes are produced. These enzymes interact with various substrates and NH_4^+, $S^=$, Ca^{2+}, Mg^{2+}, etc. are released from the organic constituents previously added to the soil. Some of these nutrients are immobilized by the microbes themselves because of increased microbial demand during the synthesis of new biomass. However if the demand is less then the amount released, net mineralization occurs. Nutrients arising in this fashion are subsequently available for any other organism, including higher plants or other microorganisms which might be growing in the ecosystem.

B. Oxidation of Inorganic Forms

Once a nutrient is mineralized, many are no longer subject to biological alteration, other than immobilization, e.g., Ca^{2+}, Mg^{2+}, Zn^{2+}, or K^+. However some inorganic forms are subject to further biological reactions. Many of these reactions involve oxidations with the subsequent release of energy for the growth of the organism. The inorganic nutrient forms most likely to be oxidized are forms of N and S. Chemoautotrophic organisms utilize this reaction for producing energy for growth. For N oxidation the process is known as nitrification, while for S it is known merely as S oxidation. Although the organisms participating in these reactions are remarkable similar, they are unique for N and S oxidation. [*See* NITROGEN CYCLING.]

In nitrification NH_4^+ can be oxidized by species representating five genera. The best known genus is *Nitrosomonas*. The end product of the reaction is NO_2; however, in most circumstances NO_2^- does not accumulate, but itself is oxidized to NO_3^- by another group of organisms, the best known of which is *Nitrobacter*. Generally the rate of the overall transformation from NH_4^+ to NO_3^- is controlled by the rate of the oxidation of NH_4^+, thus NO_2^- does not build up. This is fortunate in that much smaller quantities of NO_2^- than of NO_3^- can be toxic to higher plants. One of the side reactions of the nitrification process is progressive acidification. This can be a significant problem in agricultural soils, when ammonical fertilizers are used for a long time without a proper liming program to balance the acidification. While plants can utilize both NH_4^+ and NO_3^-, many of the agronomic crops grow better when supplied with NO_3^-. Nitrification does benefit many crops, but the primary reason for nitrification is the liberation of energy from the oxidation of the reduced N form, enabling the nitrifying organisms to grow.

Sulfur can likewise be oxidized to $SO_4^=$ by chemoautotrophic organisms. The most important genus is *Thiobacillus*. Starting from elemental S(S°), $S^=$, or any S with an oxidation state of $<6^+$, *Thiobacillus* spp. can oxidize the S for the liberation of energy and the subsequent production of the S oxides. Similar to the nitrification reaction, $SO_4^=$ is readily utilizable by plants and is thought of as a preferred S source.

On the one hand, during N and S oxidation, a highly utilizable plant nutrient is produced, but on the other hand, the anionic forms, NO_3^- and $SO_4^=$ are highly leachable. For some situations pollution of groundwater can occur and for some surficial waters nutrient enrichment, called eutrophication, occurs with the leaching of NO_3^- when N fertilizers have been improperly used. Controlling the quantity of and frequency of application can go a long way to minimize the potential for N contamination via leaching. Alternatively using a nitrification inhibitor, such as N-Serve controls the rate of NO_3^- formation. This inhibitor selectively acts on the NH_4^+ oxidizing bacteria, without affecting the NO_2^- bacteria. Although the inhibition is only temporary, the formation of NO_3^- is slowed and when NO_3^- is formed it corresponds more to the plant's need and thus NO_3^- is used by the plant as it is formed without having a large residual amount of NO_3^- found in the soil.

C. Reduction of Inorganic Nutrients

The oxidized forms on some inorganic nutrients can be subject to a series of biological reductions. These nutrients include NO_3^-, $SO_4^=$, Fe^{3+}, and Mn^{3+}. As for the oxidation of certain inorganic nutrients, which are part of the growth processes of the microorganisms, reduction is an important feature of the growth of some organisms. In order for microorganisms to grow they must have a terminal electron acceptor. For the aerobes, O_2 acts as the terminal electron acceptor and in the case of the anaerobes a variety of reduced carbon compounds functions as the terminal electron acceptor. However a group of organisms known as facultative anaerobes utilize O_2, when present, and oxidized compounds, i.e., NO_3^-, in the absence of O_2 as a terminal electron acceptor. These reactions usually occur in the following set of circumstances: an abundant supply of electron donors (reduced C compounds), absence of O_2, and the presence of an appropriate terminal electron acceptor. The best known of these reactions is denitrification.

The ability for denitrification is widespread among bacteria and on the average 10^6 denitrifiers g^{-1} occur in most soils. These organisms have the potential to produce a series of N oxide reductases when the partial pressure of O_2 is low in the system. Initially the denitrifiers utilize O_2 as their terminal electron acceptor; however, if diffusion cannot keep up with demand, the amount of O_2 keeps getting smaller and the organism is induced to produce the reductases essential for denitrification. A typical sequence might be as follows:

$$NO_3 \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$$

Each corresponding reduction step has its corresponding reductase, i.e. NO_3^- reductase, NO_2^- reductase, etc., in which the more oxidized form is used as the terminal electron acceptor. Also the three ion species to the right in the equation have the potential to escape from the soil to the atmosphere as a gas.

Denitrification can have both positive and negative aspects. On one hand, a potential leachable form of N can be removed from the ecosystem, thus preventing contamination of ground and surficial waters. However, from a plant production standpoint this series of reactions represents a loss of N which might be used for crop production. The consequence is that more N has to be applied to realize a certain level of production had denitrification not been present. Also the potential liberation of NO and N_2O to the atmosphere could have a significant impact on environmental quality.

Sulfate, Fe^{3+}, and Mn^{3+} also act as terminal electron acceptors for certain facultative anaerobes in the absence of O_2. The consequences of the reduction of these ionic forms are not as obvious as they are for denitrification, as the reduced forms are not lost from the soil ecosystem. However, the reduced forms of Fe and Mn are more toxic to higher plants than the oxidized forms and the SH adversely affects some enzymatic reactions.

D. Nitrogen Fixation

The biological reduction of N_2 to a utilizable form of N is a characteristic of only a few bacteria and is known as N fixation. Unlike the chemical reduction of N_2 which occurs at extremely high temperatures and pressures, biological reduction occurs at environmental pressures and temperatures, i.e., 1 atm and 5 to 35°C. Since this is an energy consuming reaction there must be an available energy source present (electron donor). Nitrogen fixation taking place independently of an associated plant or other microorganism is known as nonsymbiotic N fixation or, when in association with an other organism, symbiotic N fixation (discussed later).

Some of the better known nonsymbiotic N fixers are represented by such genera as *Azotobacter*, *Beijerinckia*, *Clostridium*, *Azomonas*, *Nostoc*, and *Anabena*. Nitrogen is reduced to a usable form and is incorporated into the biomass of the N fixing organism. Additions of N to the ecosystem are small until the organism dies and releases its cellular contents into the soil. Except for a few examples the amount of N fixed by these organisms is generally small and is limited by the amount of available energy present. On the average only 5–10 kg N ha^{-1} $year^{-1}$ are fixed by these organisms. An exception to this generalization is the blue green algae, represented by *Anabena* and *Nostoc*, which because of their photosynthetic ability derive their energy from sunlight. These organisms have been reported to fix up to 50 kg N ha^{-1} $year^{-1}$. Like the other nonsymbiotic N fixers any N gain is retained in the fixing cell until it dies and is released to the soil environment.

V. Plant Interactions with Microorganisms

A. Rhizosphere

One cannot understand the full potential of the microbes in the soil without an appreciation of the influence of the plant on the growth and activities of soil microorganisms. The region of soil under the influence of the plant root is known as the rhizosphere. During plant growth, various substances are exuded from the plant root including carbohydrates, amino acids, proteins, organic acids, and vitamins to mention just a few specific compounds as well as complex plant material from root abrasion and broken-off roots. These materials provide an ideal energy and C substrate for the growth and development of microorganisms. Since one of the most prominent limiting factors for microorganisms in the soil is energy and C, the release of these materials to the rooting environment causes a proliferation of microorganisms near the root.

The rhizosphere is not a fixed entity, rather it varies in time and space (Fig. 6). Other zones can be differentiated and are the rhizophane and histoplane. The former comprises the surface of the root, whereas the latter is the intracellular spaces of the plant root. The magnitude of the rhizosphere effect can be quantified by calculating a R/S, where R = number of organisms in the rhizosphere and S = number of organisms in the nonrhizosphere soil. A ratio of >1 indicates a positive rhizosphere effect. Around actively growing

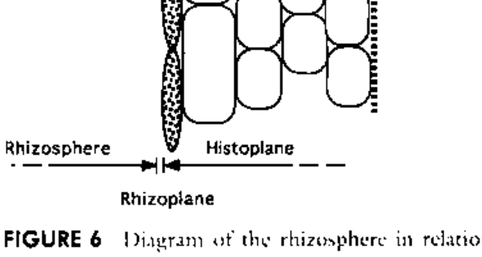

FIGURE 6 Diagram of the rhizosphere in relation to the plan root.

TABLE V

The Numbers of Bacteria in the Rhizosphere and Nonrhizosphere of Different Plants

Organisms/plant	Rhizosphere (*R*)	Nonrhizosphere (*S*)	*R/S*
	No./g soil		
Total bacteria			
Tobacco—RH.211	269.2 × 106	94.7 × 106	2.8
Tobacco—Ch.38	505.4 × 106	94.7 × 106	5.3
Flax—Bison	439.9 × 106	98.3 × 106	4.5
Flax—Novelty	2751.3 × 106	98.3 × 106	28.1
Denitrifiers			
Tobacco—Ch.38	216.3 × 106	44.6 × 106	4.8
Loblolly pine	170.0 × 103	11.2 × 103	15.2
Pond pine	25.0 × 103	2.8 × 103	8.9
Nitrifiers			
Loblolly pine	37.0 × 102	580.0 × 102	0.6
Pond pine	107.0 × 102	17.0 × 102	6.3

Adapted from Lochhead, A. G., and Wollum, A. G. (unpublished data).

plants, soil tends to have a $R/S >> 1$. Greater activity and often greater diversity of organisms is often associated with the rhizosphere and frequently means a greater abundance of nutrients for plant growth, which in turn stimulates plant growth. Likewise there is a seasonal aspect to the rhizosphere, which tends to be greatest during the warmer and wetter periods of the year. Not only does the environment itself influence the extent of the rhizosphere, but the plant itself, even to a cultivar, may exert a profound effect on microbial development (Table V).

B. Mycorrhizae

The word mycorrhiza is derived from two Greek words: *myco* meaning fungus and *rhiza* meaning root. Literally the word mycorrhiza means fungus root. Hence mycorrhiza refers to a symbiotic association between a specific fungus and the plant root, primarily the smallest order of the secondary roots. Affirming the presence of the association requires in some instances observation of distinct macrocharacteristics of the root, while for others, microscopic examination of root sections is needed for confirmation.

Mycorrhizae are a common feature on most if not all plant roots. The absence of mycorrhizae on a plant is not prima facie evidence the plant is not mycorrhizal in habit. In some instances the association is seasonal and the observer may have looked at the wrong time. Alternatively the plant may be growing off-site and there is no symbiont present or conditions may not have been appropriate for the formation of the association.

There are two primary classes of mycorrhizal associations. The first class is known as ectomycorrhizae and is recognized by observation of gross root morphologies(Fig. 7) and microscopic structures(Fig. 8). The most distinctive morphological features deal with the branched nature of the fine roots. Normally these fine roots are unbranched and quite long (1000 to 3000 μm); however, when infected with the appropriate fungus, root development is arrested and becomes branched, from dichotamously to multibranched features. In some instances the short root is almost colloroid in nature. Ectomycorrhizae are common on such plant families as Pinaceae, Fagaceae, Betulaceae, Rosaceae, and Myrtaceae, when infected by specific basidiomycetes. It is thought that the

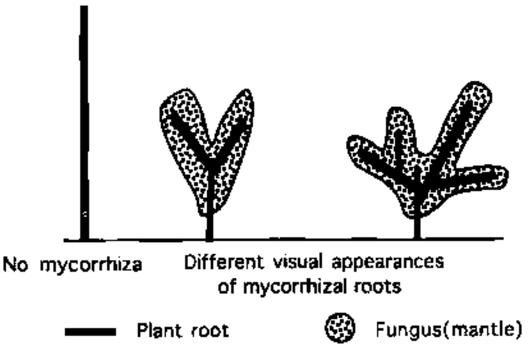

FIGURE 7 Diagram of the appearance of different roots without and with an ectomycorrhizal association.

branched development of the root arises from cytokinins produced by the plant in response to the infection which affects root development.

The microscopic morphology of the root is distinctive for the ectomycorrhizal association (Fig. 8). To the exterior of the root is a zone called the mantle, composed of fungus, often encircling the fine root. Interior to the mantle the fungus may penetrate the root and develop around the individual cortical cells. The depth of penetration and fungal development depend on the individual plant host and the infecting fungus. Regardless, the fungus does not develop beyond the endodermis of the plant root. Additionally the fungus does not grow into the root cells, remaining entirely intracellular in its infection. The growth of the fungus within the cortical region is often referred to as the Hartig's net.

The other main type of mycorrhizae are the endomycorrhizae. While there can be several endomycorrhizal types, this discussion will be confined to the one commonly known as the vesicular arbuscular mycorrhizae (VAM) and will ignore those associated with orchids (which are somewhat more specialized). Unlike the ectomycorrhizae, for endomycorrhizae, it is virtually impossible to look at a plant root and tell whether it has the associated fungus. Therefore it is necessary to look at the microscopic features of a root section and determine whether it possesses the appropriate features. If the plant is endomycorrhizal, it is likely to have vesicles (V), arbuscules (A), and intercellular hyphae. Vesicles are enlarged structures, often taking on the shape of the cortical cell, and occur at the ends of hyphae and within the cell (Fig. 9). Arbuscules, likewise, occur at the ends of hyphae within in the plant cell, but have a feathery or branched appearance. Unlike the ectomycorrhizae where the hyphae is confined to the intracellular spaces, for the endomycorrhizae the hyphae can grow both inter- and intracellularly.

The mycorrhizal association benefits the plants in many ways. Mycorrhizal plants have a better nutrient status than nonmycorrhizal plants. This is particularly true for P. It is thought the hyphae extending away from the root literally enlarge the absorbing surface for the plant enhancing nutrient acquisition. Also the mycorrhizal fungi are active producers of phosphatase enzymes and organic acids, which might enhance the solubilities of difficultly available nutrient sources of P. Other benefits also include enhanced disease protection as various mycorrhizal fungi have been shown to produce potent antibiotic substances against a variety of root pathogens. In the instance of the ectomycorrhizae one could argue that the mantle provides a protective covering about the root, thus moderating the rooting environment against extreme stresses. Finally the hyphae from both the ecto- and endomycorrhizal association may contribute to the stabilization of soil aggregates.

C. Nitrogen Fixation

In contrast to the nonsymbiotic forms of N fixation, the symbiotic association between microorganisms, with N fixing capacity and higher plants, has real potential to contribute significant quantities of N to various ecosystems. The best known of the symbiotic

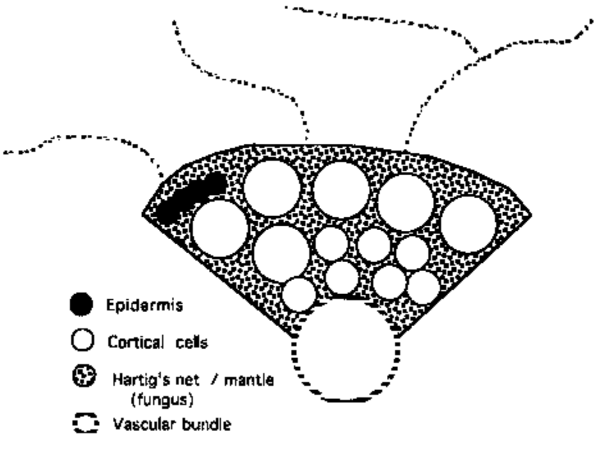

FIGURE 8 Cross-section of an ectomycorrhizal root, showing both fungal and plant features. Note the mantle is to the outer portion of the root, exterior to the epidermis and/or root cortical cells.

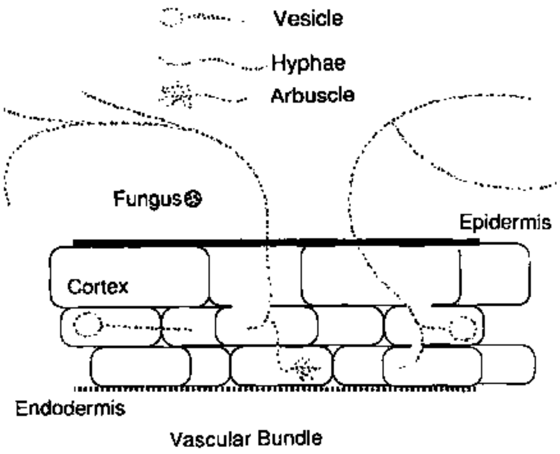

FIGURE 9 Longitudinal section of a plant root, illustrating the different components of an endomycorrhizal association.

N fixers are those found in the family Fabaceae (Leguminosae) associated with either *Rhizobium* or *Bradyrhizobium*. However there are at least 12 other plant families containing genera which will enter into a symbiotic relationship with an actinomycete called *Frankia* which are also capable of fixing N.

For both groups of symbiotic N fixers, infection occurs through root hairs or wounds on the root or both. Once within the plant root the infecting organisms develop toward the cortical regional and illicit a response from the plant which results in the formation of a nodule on the exterior of the plant root. Interior to the nodule the symbiont grows and increases in numbers. Unlike galls consisting of undifferentiated tissue forming on plants roots, nodules are actually modified roots arrested in their development. Thus nodules possess all the necessary transport features of a root and the products of fixation can easily move from the site of fixation to the top of the plant. Conversely photosynthate can be translocated from the top of the plant down to the nodule to support the energy demands of the fixation processes.

Literally 100's of kg N ha^{-1} can be incorporated into the biomass of the plant during a year's time. Initially this N is used to support plant growth, although small amounts may leak from the roots and nodules and be immediately available to other organisms in the ecosystem. However the largest share of N becomes available after the plant dies or the leaves senesce. Subsequently the mineralization of the organic residues results in an increase in the system NH_4^+ which can be used by other organisms, including plants, as a N source or as an energy source by the nitrifying organisms. In the latter instance, the NO_3^- formed can have one of several fates, such as it can be utilized as an N source, leached, or used as a terminal electron acceptor during denitrification processes. In some cropping systems, N fixed via symbiotic means constitutes the only N addition made.

VI. Future Opportunities

At the beginning of the 20th century, microbiologists realized that soil was a living and complex entity and the study of this complex system needed to be done against a background of soil fertility and crop production. This was a turning point for it made the study of soil microbiology practical in terms of an economic output. Since then, there has been great emphasis on the microbiology of N in soil systems, where it went and how much the plant actually used. Also great strides have been made in understanding the basic nature of SOM. Studies of N fixation have concentrated on the effects of inoculation with the proper symbiont and how much N could be expected from the fixation process. While investigators have contributed much to our understanding of the basic biological processes in soil, there is still much to be done.

A. Nutrients

Where it was once fashionable to study biological reactions merely from a crop production standpoint, future studies must also emphasize the environmental impact of excess amounts of nutrients in the ecosystem and how soil biological processes might be utilized to ameliorate adverse environmental conditions. For instance, it might be possible to utilize denitrification as a means for reducing the soil N concentrations when high N content waste materials are added to the soil. At the same time, however, scientists must be aware of and minimize the production of N_2O and loss to the atmosphere which might occur during denitrification.

B. Bioremediation

No longer is it sufficient to study the organic matter of the soil ecosystem just from the standpoint of its physiochemical properties. Although soil has been used for a long time as the final receptor for waste products, there must be a renewed effort to understand those factors limiting decomposition of the wastes, what constitutes a proper loading rate and what happens both to the organic and inorganic constituents of the waste product. Nutrients in organic residues need to be salvaged and reutilized, with the ultimate goal of maintaining clean air and water resources.

The potential of soil organisms to participate in the bioremediation of sites compromised by adverse activities in the environment must be maximized to the fullest. Recent disasters such as petroleum spills or reports of hazardous chemicals in ground or surficial waters underscore the importance of understanding the principles of remediation and how microorganisms might be utilized to overcome such adverse conditions. Not only are studies required on the mechanisms of remediation of different contaminants, but organisms need to be identified which have enhanced activities to degrade noxius chemicals in environmental samples. Likewise optimum conditions for organisms should be identified and implemented on a field scale allowing the establishment of the inoculant organisms in the soil which will maximize the remediation effort.

C. Biocontrol

Increasing concerns about the use of synthetic chemicals as pesticides and the potential environmental and health risks associated with many of these chemicals underscores a great opportunity to use soil microorganisms in biocontrol programs. The success of *Bacillus thuringienesis* to control the balsam woolly aphid suggests that other control opportunities exist. For instance, it may be possible to insert the *B. thuringienesis* genes for balsam wooly aphid control directly into the plant, therefore bypassing the need to use the control organism directly. However before success comes for biocontrol programs, additional organisms and use strategies need to be identified for other disease problems. Basic studies of the ecology of these control organisms may yield important clues as to how to prolong their effectiveness in the soil and plant environment. Advances in these and other areas of soil microbiology will be slow in coming unless there is a resurgence of activity in the study of the bioecology of microorganisms in the soil and rooting environment. [*See* PEST MANAGEMENT, BIOLOGICAL CONTROL.]

D. Biotechnology

In the past, the selection and use of microorganisms with some naturally enhanced property were the norm for many soil microbiologists, whether it was for pesticide degradation, biological N fixation, or some other specific function. These efforts must continue into the future and may provide part of the foundation for utilizing biotechnology in soil microbiology. Thus it may be possible to identify the genes responsible for controlling the enhanced degradation of a PCB or for a supernodulating symbiont for some important grain legume. Inserting these genes into environmentally competent organisms might overcome existing limitations of the natural ecosystem for maximizing a beneficial reaction.

Through ages past, microorganisms have been used to produce a variety of highly esthetic or useful products for both man and animal, i.e., yogurt, light-textured breads, wines, cheeses, antibiotics, etc. For their intended purposes, each microbial product makes life a little easier, safer, or more enjoyable. Today's soil microbiologists have at least two opportunities: unesthetic substrates (i.e., sewage, industrial wastes, animal manures, etc.) and limited resources. The challenge for the soil microbiologist is to use the soil as a support medium to make the undesirable or unesthetic substrates less objectionable and to exploit the residual food and energy potentials of the different substrates while getting more for less in crop production and at the same time maintaining environmental quality.

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Soil Pollution

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Glossary

Buffer capacity Capacity to retain pollutants in the soil so that the biota is protected from adverse effects and subsoil and drinking water are kept pure; buffer capacity is high with high clay and silt content and with high organic matter content

Cation exchange capacity Indicates the total of all cations adsorbed, expressed in milliequivalents per 100 g

Organic matter Fraction of the soil consisting of living organisms of the soil flora and fauna, living and dead plant roots, which may be partly decomposed and modified and newly synthesized organic substances of plant or animal origin; by conventional definition "soil organic matter" does not include coarse plant material or soil vertebrates

pH Indicates the hydrogen ion concentration, or more correctly the H^+ ion activity of the soil solution expressed as the negative logarithm

Pollutants Gaseous emissions from industry, trade, and traffic and from heating installations and waste incineration plants (sulfur dioxide, NO_x, heavy metals, non-readily degradable organic compounds, etc.), which may be emitted as gas, vapor, or dust or enter the soil mixed with precipitation; agrochemicals or other substances which are directly or indirectly applied to the soil for agricultural or non-agricultural purposes; these include fertilizers (commercial fertilizers and manure, sewage sludge, compost), plant treatment products (plant protection agents, pesticides), wood preservations, thawing agents for combatting ice and packed snow, etc.

Redox potential Defined as the electrical potential (in millivolts) which arises from electron transfer from donor to acceptor and specifies the oxidizing or reducing power of the redox system, i.e., the electrical work done

Soil pollution Deals with the contamination of soils by pollutants in the air, from the handling of environmentally hazardous substances and from waste

Soil is the natural basis of life for humans, animals, and plants. It can be impaired both quantitatively and qualitatively. Pollution affects qualitative aspects of soil.

I. Introduction

The most important soil pollutants are heavy metals, acid deposits (see Section IV), and organic substances of low mobility and degradation. Heavy metals occur naturally in soil, normally in rather low concentrations except for special geological situations (e.g., mining sites). Some of the naturally occurring heavy metals are essential for life (e.g., copper and zinc). In soil pollution studies one has to focus on heavy metals of anthropogenic origin (Table I), because these metal forms are usually more soluble than those bound in minerals and ores.

The occurrence of organic pollutants originating mainly from anthropogenic sources is either ubiquitous or specific to waste water.

The ubiquitous organic pollutants are the following:

- Polynuclear aromatic hydrocarbons (PAH), polychlorinated dibenzodioxins (PCDD), and

TABLE I
Anthropogenic Sources of Inorganic Pollutants (Mainly Heavy Metals)

	Sources								Agriculture	
Element	Industry metal[a]	Surface coating[b]	Building materials[c]	Plastics	Chemistry	Waste[d]	Fossil energy	Traffic automobiles[e]	Fertilizers[f]	Plant treatment
Lead	x	x			x	x	x	x		x
Cadmium	x	x		x	x	x	x	x	x	
Chromium	x	x			x	x			x	
Cobalt	x	x			x	x			x	
Fluorine	x		x			x	x			x
Copper	x	x			x	x			x	x
Molybdenum	x	x			x	x	x			
Nickel	x	x			x	x	x	x	x	x
Mercury	x	x			x	x	x		x	x
Selenium	x				x		x		x	
Thallium			x							
Zinc	x	x			x	x	x	x	x	

Source: Meyer, K. (1991). Bodenverschmutzung in der Schweiz. Themenbericht des Nationalen Forschungsprogrammes "Boden."
[a] Production and manufacturing.
[b] Galvanization, enameling, color spraying.
[c] Ceramics, cement, bricks.
[d] Incineration.
[e] Gasoline, abrasion of pneumatics.
[f] Sewage sludge, fertilizers, and manure.

dibenzofurans (PCDF), consequences of emissions from incineration of fossil energy carriers and mixed organic and inorganic substances from vehicles, power stations, industrial plants, and household burning. Some PAH compounds are synthesized naturally by plants and microorganisms. A geogenic basic content of PAH in soils is about 1–10 ppb.
- Phenols, polychlorinated biphenyls (PCB), phtalates, and possibly tin–organic compounds, caused by the inevitable losses, accidents, and inappropriate disposal of technical raw materials.
- Organochlorine pesticides (DDT, DDE, Lindane, etc.), formerly used as plant treatment products.

Pollutants that are specific to waste water are the following:

- Linear alkylbenzene sulfonates (LAS), Nonylphenol (NP), and other surfactants.
- Tin organic compounds from industrial use.

Until a few years ago, soil pollution was not discussed. The soil was considered to be an inexhaustible filter and a favored lasting sink for every type of pollutant. Soil protection only received political importance in the course of discussions on forest decay.

Four areas of prime importance in soil pollution are discussed in this article.

- Proportion of different sources of soil input
- Degree of soil pollution in industrialized countries
- Effects of soil pollution
- Measures against soil pollution

II. Comparison of Pollutant Inputs from Different Sources

In a study on heavy metal contents in the soils of Switzerland, the authors came to the conclusion that different site factors influenced the concentration of the five investigated metals, lead, cadmium, copper, nickel, and zinc:

- Aerosol emissions from traffic, industry, and incineration plants are mostly responsible for increased lead contents in topsoils.
- Some emission sources are locally of importance in elevating cadmium and zinc contents in topsoils. In agriculture, inputs by fertilizers (cadmium), pig slurry (zinc), and plant treatment products (zinc) have to be considered.
- Copper is mainly brought into soils by agricultural practices (pesticides, pig slurry).
- No influence of emission sources and land use can be established for nickel. As increased subsoil contents are found in the catchment area of the glacier of the Rhône in the western part of Switzerland, these contents are probably of geological origin.

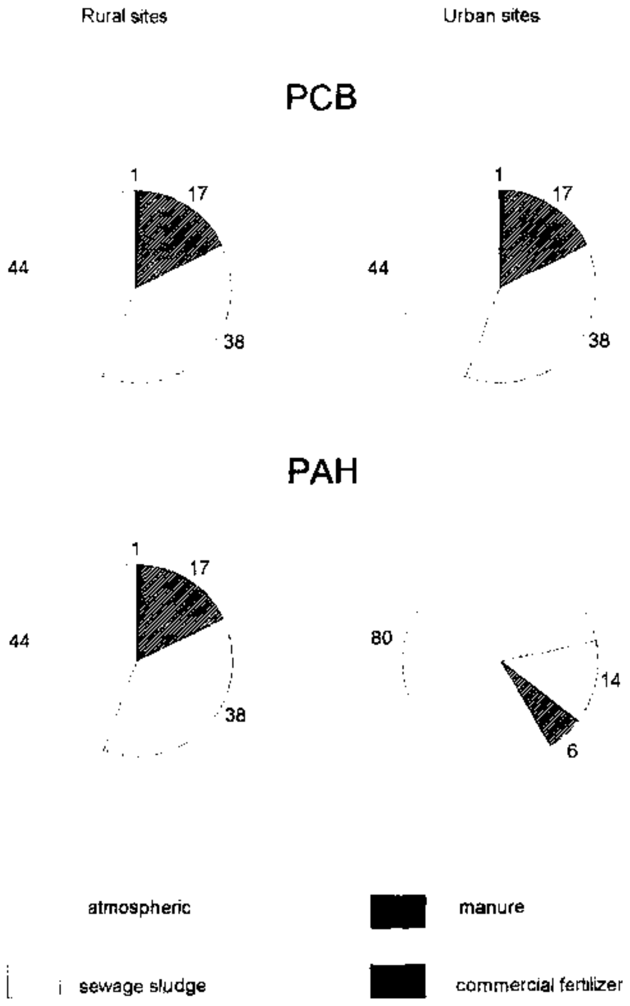

FIGURE 1 Proportions (%) of different sources of pollution of agricultural soils with PCB and PAH [From Diercxsens *et al.*, (1987). *Gas, Wasser, Abwasser*, **66**, 123–132.]

From investigations of sludged soils the approximate contributions of different auxilliary agricultural substances and of atmospheric deposition to the pollution of urban and rural soils with PCB and PAH were deduced (Fig. 1).

The most important carrier of PCB and PAH is atmospheric precipitation; in urban environments, soil pollution with PAH is practically due entirely to atmospheric input.

III. Degree of Pollution

From the already-mentioned Swiss study the conclusion may be drawn that the great majority of agricultural and forest soils contain heavy metal levels which lie below the guide values of the Ordinance Relating to Pollutants in Soil (for this ordinance see Section IV). Excess levels can be explained either by land utilization (e.g., viniculture) or by distinct emission situations. These findings were strengthened by the results of the National Soil Monitoring Network in 1993.

This pattern of great areas of low pollution in which, depending on human activities, so-called hot spots are interspersed may be very similar in other industrialized countries. However, because of the well-known bad air quality in many parts of central and eastern Europe larger areas of polluted soils have to be expected in these countries. In these regions it has been reported that the emission of soil pollutants of anthropogenic origin is about 10-fold higher than natural levels in central Europe. Deposition on forest soils is often twice as high as that on agricultural soils due to the filtering effect of forest canopies. [*See* AIR POLLUTION: PLANT GROWTH AND PRODUCTIVITY.]

Figure 2 shows an example of a polluted area due to a metal smelter. The pollution gradient of soils depends on the type of heavy metal. From Fig. 2, it can be seen that the area polluted by cadmium is larger than the copper-polluted area.

In agricultural practice it is often observed that the heavy metal content in soil goes parallel with the nutrient content. As overfertilization of garden soils is widespread, this phenomenon is very obvious in these soils. It has therefore to be concluded that many of the garden soils belong to the category of polluted soils.

Much less is known about soil pollution by organic chemicals. An interesting investigation exists in the Rothamsted Experimental Station where soils sampled since the middle of the last century were analyzed for polynuclear aromatic hydrocarbons, polychlorinated dibenzodioxins, and dibenzofurans. In the topsoil of the semi-rural site a four- to five-fold increase in the PAH content was observed within the past 100 years. This is also in accordance with findings in the United States. The PCDD and PCDF content in the same soil samples increased by a factor of 2–10.

IV. Effects of Soil Pollution

In order to define the quality of the soil and its protection in a better way, there is a need for further research on soil buffering capacity, compound speciation, soil heterogeneity, and bioavailability of pollutants. Until now, attention has been directed mainly toward

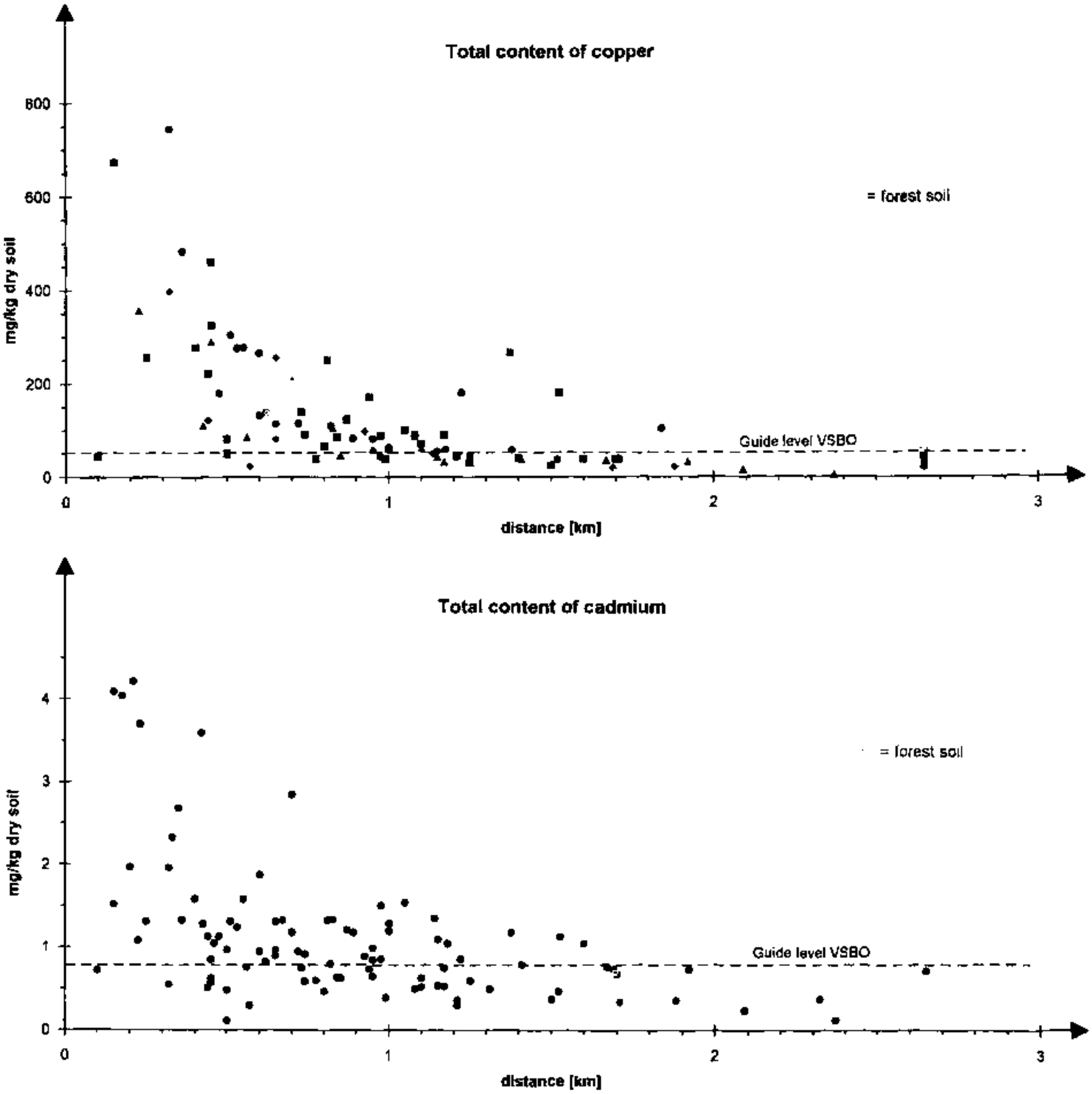

FIGURE 2 Soil pollution by copper and cadmium due to a metal smelter. Dashed line corresponds to the guide level of copper and cadmium in the Swiss Ordinance to Pollutants in Soil. [From Wirz, E. (1990). Kantonales Laboratorium Solothurn, Switzerland.]

chemical and physical properties of soils whereas biological properties have been neglected.

Usually, the soil ecosystem has a capacity to buffer and, thus, to protect the biota from adverse effects of perturbations such as chemical pollution. Only when the buffering capacity of an ecosystem is too small to retain or otherwise counteract inputs of chemical pollution will harmful effects become apparent and the ecosystem will be rendered vulnerable to adverse effects of pollution.

The most prevailing properties of soil which influence adsorption and immobilization of heavy metals are pH, redox potential, salinity, and organic matter content. Salinity directly affects soil structure; organic matter content directly affects the cation exchange capacity.

A. Soil pH

The reaction of a soil, acid, neutral, or alkaline, is expressed by pH which indicates the hydrogen ion (H^+) activity of the soil solution expressed by the negative logarithm. Hydrogen ions either are produced in internal soil processes or originate from external sources:

1. Internal Processes

- CO_2 production in respiration of soil organisms and plant roots.
- H^+ production by plant roots.
- Humification of organic matter producing fulvic and humic acids.
- Oxidation of reduced sulfur and nitrogen compounds to sulfuric acid and nitric acid by weathering or biological oxidation.

2. External Sources

- Pollution by acid deposition (mainly SO_2 and NO_x). The input of natural and anthropogenic substances from the atmosphere to the surface of the earth (soil, vegetation, buildings) is designated as atmospheric deposition. In wet depositions the substances are either dissolved or washed out as particles with the precipitation. The direct sedimentation of dusts or the adsorption of gaseous substances is defined as dry deposition. With regard to the effects on soil the acid-forming substances as SO_2 and NO_x are of prime importance. They are oxidized in the atmosphere and transformed to acids giving rise to the acid precipitation which brings a considerable amount of protons into the ecosystems.
- Ammonia emissions originating from agriculture. In regions of high animal density the emissions of ammonia can at times exceed that of SO_2 and NO_x. Ammonia is converted into ammonium sulfate in the atmosphere leading to neutralization of the acid precipitations. However, the nitrification of ammonium to nitrate in the soil causes temporary acidification.
- Manuring with acid fertilizers like superphosphate and ammonium sulfate. H^+ ions release basic cations from exchangers but pH reduction is only severe when the released cations are removed by leaching or nutrient uptake by plants which take up basic nutrient cations in exchange for H^+ ions excreted by roots. In natural soils pH drop (soil acidification) in the long term is very slight because cations are returned in the litter. The loss can be serious in intensive farming if nutrients are not replaced by manure, fertilizers, and lime.

Soil acidification due to external sources and intensive farming is delayed by a sequence of buffer reactions:

Buffer	PH Range
Carbonate	$8.6 > pH > 6.2$
Silicate	Whole pH scale (dominating buffer reaction in carbonate free soils $pH > 5$)
Exchanger	$5 > pH > 4.2$
Aluminium	$4.2 > pH$
Aluminium/iron	$3.8 > pH$
Iron	$3.2 > pH$

pH has a manifold influence on all the chemical, biological, and physical processes in soils and on soil properties. The most important effects of pH are on nutrient and heavy metal mobility. [*See* SOIL, ACID.]

The best conditions for nutrients are found in weakly acid to neutral soils (pH 5.0–7.5). Heavy metals are mobilized under acid soil conditions. It is this mobile fraction which is of the utmost concern for the biota. That is why two levels are set in the Swiss Ordinance Relating to Pollutants in Soil: total heavy metal content to limit the load to a safe level and soluble heavy metal content to assess the bioavailability, determined in a neutral salt extract. Increased metal concentrations in plants, yield reduction, or change of the soil mineralization potential (e.g., its ability to degrade harmful chemicals into harmless inorganic end products) may be cited as important effects of enhanced concentrations of this bioavailable fraction.

As the pH falls below 4.2 (aluminum buffer range) the leaching of aluminum, present as a natural immobile component of soil, is greatly increased. Adverse effects in the ecosystem, such as tree damage and fish kills, begin to be manifested.

B. Redox Potential

Redox potential is high in well-aerated soils with much O_2 dissolved in the soil solution and a high proportion of oxidized compounds (Fe and Mn oxides, hydroxide, nitrate, sulphate), i.e., well-drained soils with a low water table and low content of easily decomposable organic matter.

Redox potential is low in O_2-deficient soils with much reduced compounds (Fe^{II}, Mn^{II}, S^{2-}) and easily decomposable organic matter, i.e., especially in hydromorphic soils. The influence of water in these soils

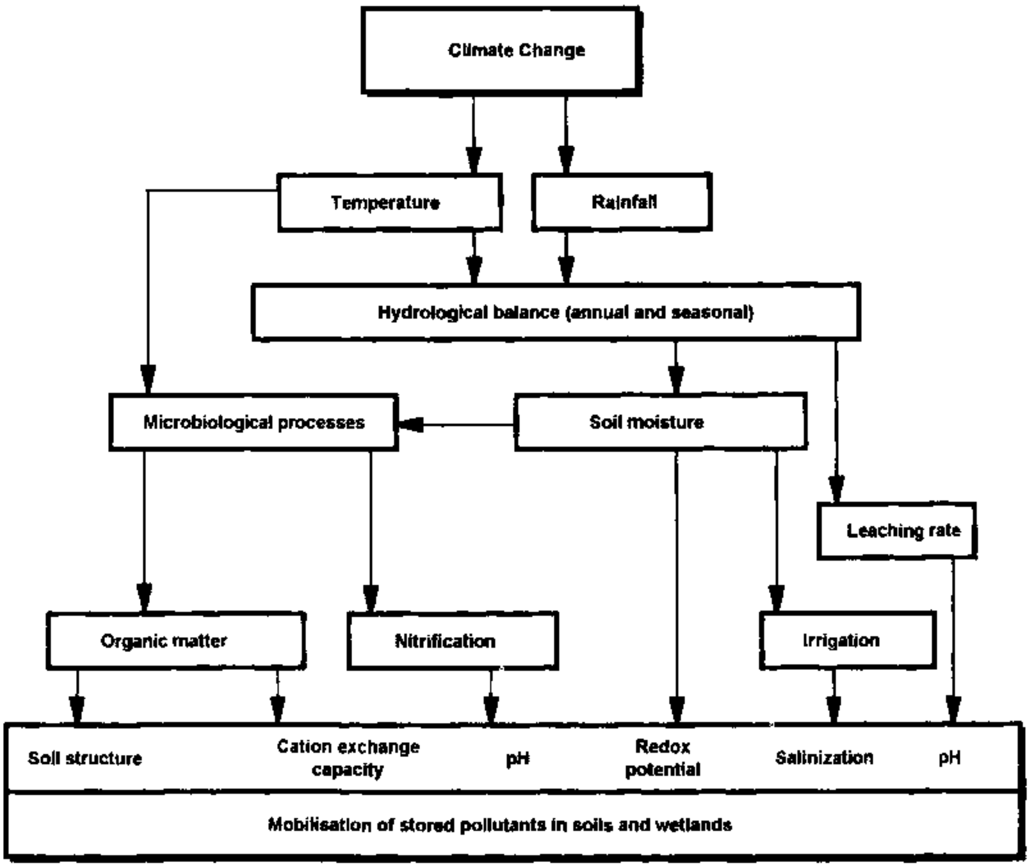

FIGURE 3 How climate change can affect the mobility of heavy metals stored in soils and wetland. [From Stigliani and Salomons, W., submitted for publication.]

is either permanent, due to groundwater, or temporary, due to surface water caused by impeded drainage. [*See* Soil–Water Relationships.]

Soils with high amounts of substances that can be oxidized and reduced are poised, i.e., well-buffered against severe change in redox potential in either direction.

Since H^+ ions are produced by oxidation, pH declines as redox potential increases. The ecological significance of redox potential lies in its effect on nutrient availability. Further, the solubility of heavy metals either adsorbed or occluded in iron and manganese oxides is increased by the reduction of these oxides. [*See* Soil, Chemicals: Movement and Retention; Soil Chemistry.]

C. Changes of Soil Properties

Important factors which can change soil properties are temperature and rainfall. Therefore, the so-called climate change threatens to create soil property alterations, as shown in Fig. 3.

Higher soil temperatures increase microbial decomposition leading to a decrease of the soil organic matter content. In contrast, increasing soil moisture has the effect of increasing organic matter content (and vice versa). [*See* Soil Microbiology.]

Decreases in the organic matter content of soils cause increases of *heavy metal* mobility due to enhanced erosion and diminished cation exchange capacity, which results in less adsorption. Drying out of wetland soils can mobilize insoluble sulfides which are transformed into soluble sulfates at higher redox potential. Soils with increased salinity have a reduced capacity to store heavy metals. Such soils are formed in regions where the rate of evapotranspiration is greater than the rate of precipitation and saline water is used for irrigation.

From these observations, it is apparent that the capacities of soils to store heavy metals would be significantly reduced under warmer, drier conditions.

The most vulnerable area are those with both high accumulated chemical loads and high storage capacities.

D. Organic Chemicals

PAH, PCB, PCDD, and PCDF have low degradation potentials, while the monocyclic aromatics and the short-chained halogenated aliphatics are readily degraded and moderately leached.

Possible transfers into plants and animals may be assessed by the use of the octanol–water partition coefficient (K_{OW}). K_{OW} is defined as the ratio of a chemical concentration in octanol to that in the aqueous phase of a two-phase octanol/water experimental system at equilibrium:

$$K_{OW} = \frac{\text{concentration in octanol phase}}{\text{concentration in aqueos phase}}$$

Log K_{OW} describes the lipophilicity and hydrophobicity of the chemical in question.

Potential for retention by root surfaces can be envisaged as a sorption process similar to that described for soils. Consequently "high," "medium," and "low" categories are defined as log K_{OW} values of >4.0, >2.5, and <2.5, respectively. The high retention category is intended to identify those compounds which contaminate root crops at the surface.

For potential root uptake and translocation the following categories are used:

Category	Values
High potential for root uptake and translocation:	Log $K_{OW} < 3.5$ and $T_{1/2} > 50$ days
Moderate potential:	Log $K_{OW} < 4.5$ and $T_{1/2} > 10$ days
Low potential:	Log $K_{OW} > 4.5$

Potential transfer to animal tissues via soil ingestion will depend on compound persistence in soil and on bioaccumulation potential in terrestrial ecosystems.

V. Measures against Soil Pollution

Because the purification of soils, contrary to air and water, is difficult or even impossible, preventive measures are of prime importance in qualitative soil protection. Once the soil fertility is impaired, its recovery (i.e., sanitation) is very limited. [*See* SOIL FERTILITY.]

To protect soil, the following measures have to be considered:

- Limits on pollutant emissions from both nonagricultural and agricultural sources.
- Application rules and advisory services for farmers.
- Properly organized waste management systems.
- Surveillance systems for monitoring the level of pollution in the soil.

VI. Conclusion and Summary

Whereas the origin of soil pollutants is known to a great extent, specific gaps in knowledge remain about the fate of pollutants (mainly organic chemicals) in soil. Moreover, the effects of pollutants in biological soil properties are not sufficiently understood. While reducing measures are becoming effective for heavy metals in many countries, the efforts to reduce acid atmospheric depositions have been much less successful. Therefore, research has to be intensified in the risk assessment of soils that have been polluted in former times and in soil acidicification processes. Finally, questions about the influence of climate change on the storage capacity of pollutants in soil may gain growing interest.

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Soil Testing for Plant Growth and Soil Fertility

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Glossary

Available nutrient That portion of an essential element in the soil that is readily absorbed into plant roots

Cation exchange capacity Quantity of (exchangeable) cations that a soil can adsorb to its negatively charged sites, usually expressed in centimoles$_c$ per kilogram of soil

Chelates Certain organic molecules bonded to one of many metals, particularly iron, zinc, copper, and manganese; a molecule may have several bonds to its metal and natural chelates may be soluble or insoluble; fertilizer chelates are soluble and help to mobilize metals in soil solution

Field correlation Studying the relationship between soil test values from the laboratory with the plant's response to added fertilizer in hundreds of field plots on those same soils

Humus Organic matter remaining in soil after the major portion of added residues (roots, tops, manures) have decomposed

Ions Atoms or groups of atoms that are negatively or positively charged, by gain or loss of electrons

Labile The quantity of a nutrient which is or will become available during a growing season

Peds Units of soil structure formed by natural processes (i.e., blocks, prisms, granules, plates)

Quick tests Term for mostly laboratory tests that can be done quickly to evaluate the soil properties and fertility needs

Soil structure Arrangement and combination of sand, silt, and clay particles into large aggregates or peds (i.e., granular structure, blocky structure, prismatic structure)

Soil texture Terms to describe the proportions of sand, silt, and clay (and coarser fragments) in a soil; a "loam" has about equal physical properties from its sand, its silt, and its clay

Soil testing is a general term for analyses of soil samples to obtain useful information about that soil. Soils are analyzed to permit correction of deficiencies or to correct excesses of harmful constituents. Deficiencies are usually those of nutrient elements; harmful constituents may be strong acidity, toxic elements, or elements taken up by plants that are harmful to animals that consume the plant materials. With the advent of large world populations, wastes have multiplied. Many soil tests are now involved in the determination of the extent of pollution and to reclaim polluted or damaged soils. This section contains soil tests for correcting soil fertility, and the soil tests used in the monitoring and correction of polluted soils.

I. Important Properties of Soils

Soil is the natural media supporting land plants and supplying water and 13 of the 16 essential elements to plants. A few plants benefit from an additional few elements, which are also derived from the soil. In the process of providing and supplying these plant needs, the physical and chemical soil properties can exert dominant influences. The *physical properties* include soil texture (proportions of sand, silt, and clay), soil structure (the shape and porosity of masses of soil particles cemented together), soil aeration (the ease of air exchange into the soil), mineralogy (the kinds

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of minerals comprising the soil), soil temperature, and the water relationships in the soil. *Chemical properties* include the soil pH (acidity or alkalinity), the concentrations of available nutrients, the presence of toxic concentrations of certain elements, the amount of humus (residue of plant materials after extensive decomposition), and chemically active mineral surfaces that adsorb organic substances and soluble ions. [*See* SOIL CHEMISTRY.]

In addition to the physical and chemical properties, the kinds and amounts of *microbes* (thousands of species of bacteria, actinomycetes, fungi, algae, and others) and the large *animals* (earthworms, nematodes, amoeba, insects, slugs) all affect growing plants. Microorganisms decompose soil humus, and minerals weather (decay) releasing nutrients. Certain bacteria make critical chemical conversions in soils (carbon monoxide to carbon dioxide, changing nonusable gaseous dinitrogen of the air to usable amino acids, oxidizing undesirable sulfide to usable sulfate, and many other changes). [*See* SOIL MICROBIOLOGY.]

Thus, soil tests, which are used to predict the availability of one or more deficient nutrients, may indicate which nutrients are adequate or deficient. Nevertheless, the growth of the plant will depend on the suitability of the soil for plant growth. The soil must have adequate oxygen to roots, warm temperatures, adequate but not too much water, a suitable soil pH, adequate nutrients, and many additional factors. [*See* SOIL FERTILITY.]

II. Physical Soil Properties

Soil texture is often a controlling plant growth factor. Soil texture is a measure of how clayey or sandy a soil is. A clayey soil may be very hard when dry, sticky when wet, poorly aerated, and poorly permeable to water. Plant roots may not grow very deep in clays because of poor aeration; their hard crusts when drying may inhibit seedling emergence. Clayey soils have more pore space than do sands, but the pores are smaller and slower in transmitting air and water. Clayey soils hold more water and, in temperate climates, will warm up more slowly than do sandy soils. Clayey soils are more difficult to till, often requiring that it be done within a relatively narrow range of water content.

A soil's texture can be estimated by feeling the soil with ones' fingers when it is dry and as water is added gradually. The exact amounts of clay, silt, and sand in a soil are seldom important. The general texture is, however, important and can be measured by various methods. Laboratories can measure different sand sizes and coarser fragments (gravel and stones) by sieves. Contents of sands (2 to 0.05 mm diameter), silt (0.05–0.002 mm), and clay (less than 0.002 mm) are readily measured by the amounts that settle out of a water suspension after various times. Approximate rates of fall in water for some of the fractions are

0.5-mm-diameter (medium) sand	21.8 cm sec^{-1}
0.2-mm-diameter (fine) silt	3.5 cm sec^{-1}
0.01-mm-diameter (medium) silt	0.52 cm min^{-1}
0.002-mm-diameter (coarse) clay	0.021 cm min^{-1}
0.0002-mm-diameter (fine) clay	0.30 cm day^{-1}

The amount of soil that falls, after various selected periods of time, can be measured by the pipette method which removes a known volume of the suspended soil at the calculated depth of settling. A simpler method, the hydrometer or Bouyoucus method, measures the lessening solution density with a hydrometer as soil particles fall out of a uniform suspension.

The 12 textural classes most used are shown on the textural triangle in Fig. 1. To determine a texture from the percentages of sand, silt, and clay, adjust the triangle so that the 100% of the fraction being used (say, clay) is at the top and read the percentages of the fraction (clay, in this instance) along lines parallel to the base of the triangle. Do this for two of the fractions. Where they intersect is the soil's texture. All three fractions will intersect at the same point because the textural class assumes that sand + silt + clay = 100%.

Further textural detail is provided by indicating sand sizes, i.e., *fine* sandy loam. If particles larger than sand (coarse fragments) are present, these are named *gravel* (0.2–7.6 cm diameter), *cobble* (7.6–25 cm), *stone* (25–60 cm), and *boulder* (over 60 cm diameter). A sandy loam with coarse fragments (by volume) would be named as follows.

Less than 15% coarse fragments	Sandy loam
15 to 35% gravel-size fragments	*Gravelly* sandy loam
35 to 60% gravel-size fragments	*Very gravelly* sandy loam
Over 60% gravel-size fragments	*Extremely gravelly* sandy loam

The sand sizes and coarse fragment contents cause differences in water movement, water retention, and tillability of the soil. Knowing the kinds and amounts of clay help the analyst to predict stickiness and support strength of the soil when it is wet, hardness when

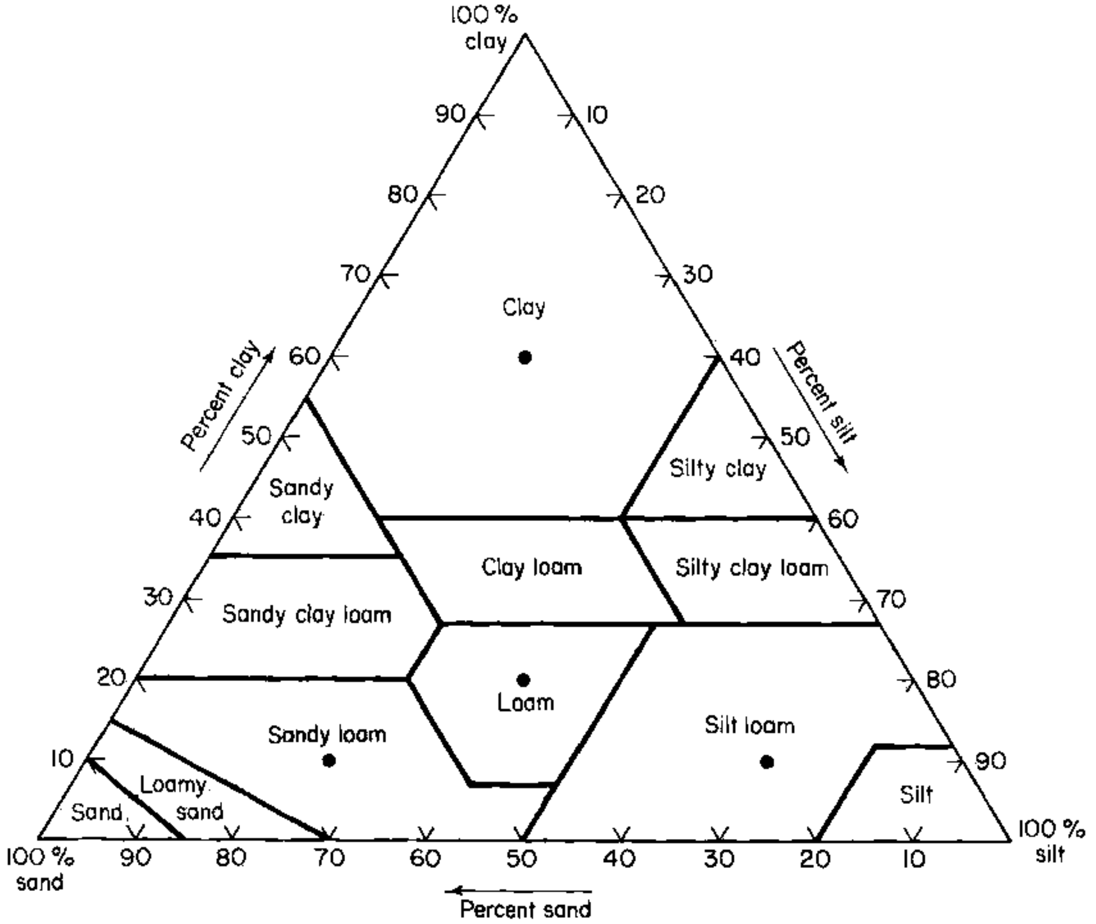

FIGURE 1 Textural triangle for soils.

it is dry, cracking when it is dry, and permeability to water and air.

Soil structure (the term *ped* is used to indicate a unit of soil structure) develops over decades and centuries of time as soils are wetted and dried, swell and shrink, and develop the organic "cements" (plus clay, iron oxides, and silica as cements) that hold (cement) particles together. Structural units are destroyed by decomposition of the humus cements or newly formed by additional humus products and mineral solution and resolidification (precipitation). Soil mixing at the surface (animals, tillage) causes surface soil structural units to have a somewhat spherical shape (granular peds), from a few 10ths millimeter to several millimeters in diameter. Vertical cracks and some horizontal cracking of a soil mass eventually produces vertically elongated prisms (prismatic or columnar) and cube-like (angular blocky or subangular blocky) shapes that range from about 5 to over 100 millimeters across. Compaction or other causes may form horizontal plates (platy) of about 1 to over 10 mm thick. Platy structure is common below plowing depth (plow pan) and near the surface of noncultivated land as a result of compaction by animals or equipment and of frost action.

Good structure, except possibly platy structure, increases pore sizes between ped units, allowing better aeration, and water and air flow, as well as providing large spaces into which roots can grow. In clayey soils most air and water flow is down through the large pores (cracks) between peds. Tillage can reduce soil structure by mechanical breakage and speeding up humus decomposition (structure cement decomposed). Structure development in clays is slower but eventually is stronger than that in sandier soils. Sands seldom develop much structure, but the pores in sands are already large, and they easily transmit air and water.

Soil aeration indicates the ease with which air can exchange with the soil atmosphere to supply needed oxygen and to remove the carbon dioxide produced as roots respire and humus is decomposed. Sands are well aerated. Air exchange is reduced by poor structure and high clay contents and by excess water that fills the smaller pores and "bottleneck" portions of pores. Oxygen does not move readily through even thin films of water. The reduced aeration in water-blocked pores hinders the oxygen supply to roots and slows growth or causes death of most plants. Only relatively few plants (rice, for example) can bring oxygen down to their roots through their stems.

Soil mineralogy is the combination of minerals making up the bulk soil. Literally hundreds of minerals are present, each one a source of one or more of the approximately 20 important elements in soils. The quantities and kinds of minerals determine the supply of available nutrients and the toxicities that a soil supplies. The kinds of rocks and minerals also affect soil texture (sandstones and quartzite produce sandy soils, limestones and shales produce clayey soils). Some minerals (micas and feldspars) readily produce clays as they weather. Unfortunately, although the soil's fertility is related to the soil's mineralogy, the quantitative relationship of identified minerals and available nutrients is not well documented. Identification of the mineral "suite" in a soil involves microscopic and X-ray diffraction studies and is costly and time consuming. Few mineralogical analyses are done in fertility testing.

Water infiltration, percolation, and drainage are essential to allow rain and irrigation water to penetrate into soil. To avoid excess water (waterlogging), soils must allow water to drain away (percolate). Percolating water does dissolve and remove many soluble nutrients, particularly nitrates and sulfates. Leached soils may lose much of their fertility by this percolation action (leaching away soluble nutrients). Soils with large pores (sands and well-structured soils) are more easily leached than are clayey soils. [*See* SOIL DRAINAGE; SOIL–WATER RELATIONSHIPS.]

Water storage in the soil is crucial to plants in less humid climates; roots absorb water stored in soil pores. Where rainfall is infrequent, soil water must be replaced by irrigation. The quantity of water needed ranges from about 0.3 to 1.0 cm daily in warm growing periods. Sandy soils may store only about 1 to 3 cm of usable water per 30 cm (1 foot) of depth; clayey soils and clay loams may store from 3 to 6 cm of usable water per foot. As this water is absorbed, many nutrient elements dissolved in the water are carried to the plant root. Most or all of the nitrogen, sulfur, calcium, magnesium, boron, and a few other nutrients are supplied to the root surfaces in this absorbed water.

As the water in the upper foot or so of soil is used, the plant may still be able to absorb adequate water from deeper soil layers and continue to grow. However, since the surface soil layer has most of the soil humus (which supplies nitrogen plus other nutrients) and is where fertilizer is applied, water movement in the surface soil supplies many more nutrients than does water in deeper soil layers. As a soil layer dries out, the nutrients contained in that layer become less and less available. If a surface soil dries to 30 or 40 cm deep (the top 30 to 40 cm is where most of that plant's roots are growing), the plant must absorb enough water to grow from deeper soil layers; the nutrient supply will be reduced during the time water is mostly supplied from deeper soil. [*See* SOIL GENESIS, MORPHOLOGY, AND CLASSIFICATION.]

III. Chemical Soil Properties

Soil acidity alters nutrient availability and element toxicity. In soils, soil acidity or alkalinity is referred to as "soil pH" or "soil reaction." Soils that have large amounts of sodium and calcium tend to be alkaline or basic. When soils have been leached through centuries of time in high rainfall areas (over about 500 mm or 20 inches annual rainfall), soils lose much of the sodium and calcium and accumulate hydrogen ion (H^+) from the weak acid of carbon dioxide in water. The common minerals in soils also contain aluminum. The soluble aluminum in the soil forms an acidic aluminum species that adsorbs to the cation exchange capacity sites. When the soil acidity reaches a "strongly acidic" pH of about 4.5, enough soluble aluminum exists to be toxic to many plants. The most common growth problem in strongly acidic soils is aluminum toxicity; too much soluble aluminum is toxic to plant roots and slows microbial processes as well. [*See* SOIL, ACID.]

Acidic soils can be improved by neutralizing some of the acidity with an added "lime." The most common and cheapest lime is powdered limestone, but many alkaline substances (calcium oxide, wood ashes, marl, and powdered egg and sea shells) can be used. The lime is mixed into the soil at rates of about 1 to 10 metric tons per hectare every second, third, or fourth year. The amount and frequency of lime addition depends on (1) the initial acidity of the soil, (2) the total cation exchange capacity or acidic sites occupied, and (3) the sensitivity of the crop to be grown to acidity. Soil pH is usually adjusted to pH above 5.5, commonly near to pH 6.0. There are some "acid-loving" plants that do best when the pH is kept low (azaleas, blueberries, cranberries, pineapples, tea).

Soluble salts are an increasing concern. Soluble salts are the soluble remains of weathered rocks. They are mostly the ions of calcium, sodium, magnesium, chloride, sulfate, and bicarbonate. Too much soluble salts hinder water absorption by plants and cause the plant to die. One reclaims salty soils by leaching the salt from the soil. As environmental concerns increase, however, there is an increasing support to limit leaching of the salts from soils because the salts must end up in ground or surface waters. Accumulations of soluble salts are a problem; what or how to reclaim the land and dispose of the washed-out soluble salts is no less a problem.

Measurement and evaluation of the soil salt content is fairly simple. The electrical conductivity of the extract from a wetted soil is measured. The conductivity, in decisiemens per meter (dS m^{-1}) indicates the salt content. The approximate scale below is a general guide for conductivity of the extract of a saturated soil paste:

Less than 2 dS m^{-1}	No plants affected
2–4 dS m^{-1}	A few plants have reduced growth
4–8 dS m^{-1}	Many plants have reduced growth
8–16 dS m^{-1}	Most plants have reduced growth
16–30 dS m^{-1}	Most plants die or have less than 50% of normal yields.

The tolerance of plants varies enormously; a few common ones are listed below, with tolerance increasing down each list.

Least tolerant 2–6 dS m^{-1}	Moderate tolerance 6–10 dS m^{-1}	Most tolerant 10–20 dS m^{-1}
Strawberry	Blackberry	Tomato
Raspberry	Peach	Broccoli
Avocado	Onion	Spinach
Beans	Many fruits	Fig
Carrot	Pepper	Cantaloupe
Peanut	Soybean	Beets
Clovers	Lettuce	Sugarbeet
	Corn	Cotton
		Barley
		Date palm

The removal of soluble salts is done by leaching. Unfortunately, some clayey soils of high sodium content have poor permeability. In such soils, the major problem is one of soil porosity—the soil does not transmit water well enough to allow easy leaching. Soils of this type must have internal permeability increased, a costly and slow process. Mixing the profile (tillage), mixing in gypsum, or laying shallow drainage lines are all used on various soils.

Cation exchange capacity (CEC) involves a chemical surface reaction. Clays and humus have structural features that cause them to have "net negative charges." These negatively charged sites attract and hold positively charged ions. The ions most often held in the largest amounts are calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), aluminum ($Al[OH]_2^{+}$ or Al^{3+}), potassium (K^{+}), and hydrogen (H_3O^{+}). Small amounts of several other cations also are held. The quantity of the CEC in soils varies from low values in sands to higher values in clays; the highest values are found in organic soils. If all the sites held calcium, the soil's exchange sites per 30 cm of depth could hold from somewhat over 1000 kg per hectare in low-CEC soils to over 10,000 kg of calcium per hectare in soils with a relatively high CEC. These exchangeable ions are not easily removed by leaching but can be replaced by other cations that are soluble in the soil solution, such as potassium or ammonium fertilizers or lime. [*See* SOIL, CHEMICALS: MOVEMENT AND RETENTION.]

IV. Measuring Available Nutrients

The objectives of soil fertility testing include (1) characterizing the soil to identify any problems of acidity, drainage, texture, or toxicity, (2) assessing the status of the soil's plant nutrients to know what is deficient, and (3) predicting the amount to add of each nutrient element which tests show to be deficient. The tests suitable for use are numerous. The major difficulty in any test lies in interpreting the meaning of the values obtained. A soil sample could be extracted with a variety of strong acids, weak acids, diluted acids, salt solutions, oxidizing or reducing solutions, and alkaline solutions. Each extractant would extract different amounts from subsamples of the same soil. Which value would be correct? Only a good correlation study can provide an answer.

Correlations of laboratory tests to field plot yield data are the most essential parts of the testing program. If the laboratory test values for nutrient "A" are large, the field plot plants should have enough of nutrient "A" in the soil and should not respond to nutrient "A" added as fertilizer. If the laboratory test values for "A" are small, the soil should be low in nutrient "A" and field plot plants should respond to considerable amounts of fertilizer containing nutrient "A". [*See* Fertilizer Management and Technology; Soil Management.]

The only suitable lab texts are those whose values for a soil are inversely proportional to the fertilizer needed for good growth in field trials on that soil. Thus, many different laboratory tests might individually be well correlated with plant response in field tests and could be used. The perpetual search is for a well-correlated test for each plant nutrient which is quick, cheap, and easy to do but which is not susceptible to easy errors.

Nutrients which are not deficient in most soils are more difficult to correlate with laboratory tests. There are relatively few soils with obvious micronutrient, sulfur, and magnesium deficiencies on which to do the field testing. Thus, soil tests for deficiencies of many micronutrients have been correlated to only a relatively few soils; these tests are only moderately well or poorly established.

Nitrogen (N) is the most often deficient nutrient. Thus, a good predictive laboratory soil test for the amount of N needed in a soil is eagerly sought. Unfortunately, a good, widely used quick soil test for needed N is not presently available. It is the major element that needs to be added to increase growth of lawns and most other crops. N-fixing legumes (bacteria in plant roots utilize atmospheric N_2, which most plants cannot do) obtain some or all of their N by using atmospheric dinitrogen (N_2). The atmosphere has about 79% N_2. In localized areas where intensive field plot tests have been carefully made, measuring soluble nitrate to a depth of 61–92 cm (2–3 feet) has been quite satisfactory. Unfortunately, people do not like the work required to sample to those depths; most soil tests are on the 0–30 cm (1 foot depth).

The reasons why a good soil test for N has been elusive are that the N cycle is very complex—many things can happen to N, sometimes very quickly. First, temporary water logging in a soil for a few days can cause nitrate to be volatilized into the air as dinitrogen gas (denitrification). Second, microorganisms decompose soil organic materials. Most natural soil N is that N released from organic materials (humus, manures, plant wastes) as they undergo decomposition. Decomposition is accomplished by microbes whose activity is regulated by adequate water, temperature, and aeration. The nitrogen contained can be released for plant use if soil N is already high or the N released can be absorbed by organisms to become unavailable microbial tissues if soil N is low. Third, soil nitrate is very mobile in soils and is readily washed into groundwaters by percolating rains or excess irrigation. Fourth, ammonium N fertilizers (ammonium nitrate, ammonium sulfate, urea) applied on the soil surface of arid region (alkaline) soils can be lost by volatilization of the N as ammonia gas (NH_3). These many possible transformations or losses of added N fertilizers make it difficult to predict what the efficiency of added fertilizer N will be. These changes of N in the N cycle are difficult to evaluate accurately when on the site; they are even more difficult to evaluate by the soil tester in a laboratory far away. The analyst has no control over water applied, rainfall, temperature, the physical condition (aeration), or the management of the soil. [*See* Nitrogen Cycling.]

Phosphorus (P) and *potassium* (K) soil tests are widely used and accepted. These two elements are the second and third most often deficient plant nutrients. Phosphorus has low solubility in soils and can be deficient in any climatic area, in sandy soils, in intensively weathered soils (stable tropical lands), and in soils with crops having high P demands (vegetables, legumes, potatoes). Only about 10 to 30% of added soluble P fertilizers is used by the crop to which it is added; the rest forms low-solubility mineral precipitates, but stays in the soil. Thus, three to five times more P is added than is used. Yet, the carryover P (that added but not used that season) has little of it available to the next crop. The soil P content will gradually increase in regularly fertilized soils.

Maximum conversion of soluble P to low-solubility P compounds occurs in soils with high contents of soluble calcium or lime (calcium carbonates) and particularly in soils high in free iron oxides (sesquioxides). Weathered soil materials especially in highly weathered tropical soils are high in iron oxides. The weathered tropical soils can have as high as 70 to 80% sesquioxides, to which P readily and strongly adsorbs. Only small portions of added P remain soluble to be used during the growing season. In such soils, placing the P in small "bands" 5 to 10 cm deep and 5 to 10 cm to the side of the planted seed is often the most effective application. The major chemical extractants used for phosphorus soil tests are the following:

- For acidic soils
  Bray No. 1: dilute HCl and dilute NH_4F
  Mehlich No. 1: dilute HCl and dilute H_2SO_4

- For alkaline and calcareous soils
  Olsen test: dilute $NaHCO_3$ at pH 8.5
  Ammonium bicarbonate at pH 7.5

Each of these extractants is correlated with field trials to establish a table of test values as criteria of the fertilizer P needed for various crop groups.

Potassium (K) forms mostly soluble minerals in soils even though its common mineral sources (micas and feldspars) have K in a very low-solubility form. Because K is so slowly soluble from its source minerals, the major K source for a crop is the soil's soluble and exchangeable K. The negative charges on clays and soil humus hold positively charged ions (called cations, cat-i-ons). Most of the K used by plants is from soil's exchangeable K plus any soluble K in the soil solution. Almost any test which measures mostly the exchangeable K has given fairly good correlation to the needs for added K fertilizer. The most common extractant for exchangeable K is ammonium acetate, but various salt solutions, dilute strong acids, and the ammonium bicarbonate extract used for the P test have all been used.

Soils needing added K are usually sandy soils and those acidic soils in humid climates. In arid (irrigated) regions, little or none of the K solubilized by weathering is removed by leaching (percolating rainwaters). However, in high-rainfall, permeable soils, rains can wash out K during the decades and centuries of weathering and leaching. High-K-demand crops (potatoes, bananas, and other sugar- and starch-producing crops) may benefit from additions of fertilizer K even though the soils are normally adequate in K for most crops.

Sulfur (S) is much less likely to be deficient than are N, P, and K. In the past several decades, considerable sulfur was added to soils (1) as a constituent of the fertilizers ammonium sulfate, potassium sulfate, and regular superphosphate; (2) as fallout of "acid rain," which contains sulfuric acid; and (3) as components of some pesticides. These sources of S are still added but less often and in lesser amounts. The higher crop yields and fewer incidental S additions have caused S deficiency to be more common.

Predicting S needs by soil tests has many of the same problems as those mentioned for N. The S cycle has several kinds of losses. Sulfur is volatilized as sulfide gas in anaerobic waterlogged soils, the soluble "end product"—sulfate—is readily leached, and sulfur released during decomposition of organic matter can be made into bodies of new microbes. Because S is needed in much smaller amounts than is N and because S does come from both humus and various minerals (gypsum, pyrites, others), S is less often deficient than N, P, or K. Consequently, less work on soil tests has been done for S than has been done for N, P, and K.

In some areas where S deficiency is widespread and economically quite important, adequate soil tests have been developed. They are somewhat similar to those for N, which measure the soluble end product of microbial action. For sulfur, this end product is sulfate. The amount of soluble sulfate in the top 61 cm (2 feet) or 92 cm (3 feet) has given the best correlation to plant response in field plots. Unfortunately, soil tests to evaluate S needs are not usually reliable. Often information on the humus content and soil texture is useful; S deficiency is most likely in more sandy, low-humus, acidic soils.

The *micronutrients* boron (B), iron (Fe), zinc (Zn), copper (Cu), manganese (Mn), chloride (Cl), and molybdenum (Mo) are much less often deficient than are N, P, K, S, Ca, and Mg. In various high-rainfall, leached soils boron may be largely washed away and be deficient. Its mineral source tourmaline is of very low solubility; its mineral fertilizer source is borax, a water-soluble deposit. Overall, B is the most commonly deficient micronutrient. Its most common soil test—soluble B in boiling water—is a good test but not convenient to do. Other tests are being studied.

A spectacular and colorful plant deficiency is caused by inadequate iron (Fe); the young leaves of the plant become chlorotic (yellowed) between veins while veins remain green. In extreme cases, leaves may be almost white. Iron deficiency is poorly understood and its correction is the most difficult of all nutrients to accomplish. It is fortunate that relatively few soils and crops have severe Fe deficiency. Most soils have several percentage Fe contents but iron compounds are extremely low in solubility. Plants with Fe deficiency may sometimes contain more Fe than do other plants which are not deficient. Why the plant is deficient is usually unexplained. Because Fe forms such low-solubility compounds when added to soil, correcting deficiencies is usually done by applying a soluble Fe to the foliage. Organic materials (chelates) that bind the Fe keeping the Fe mobile are the most common carriers of iron.

Diagnosing or predicting iron deficiency by soil testing is difficult. Most soil iron moving to roots is believed to do so as naturally produced chelates. So, soil tests employ an extracting solution containing a small concentration of the chelate DTPA (diethylenetriaminepentaacetic acid). Typical extraction values in DTPA for Fe, Zn, Mn, and Cu are shown below:

	Fe	Zn	Cu	Mn
		(mg kg^{-1})		
Low (deficient)	0–2.5	0–0.5	0–0.2	0–1.0
Marginal (barely adequate)	2.6–4.5	0.6–1.0	?	?
High (sufficient)	4.5+	1.0+	1.0+	2.0+

The tests are fair to good where well correlated to field plots. However, there have been limited numbers of studies done and there are relatively few soils exhibiting iron deficiencies. The quality of the soil tests are localized to areas where good correlation work has been done. Alkaline (arid-region) soils are more likely to have iron deficiency than are acidic (humid area) soils. Deficiency is common on peaches, raspberries, some soybeans, roses, and several other ornamental flowers and evergreens.

Soils tests for Zn, Cu, and Mn also are somewhat approximate; they are valuable where good correlation field studies have been done. Values for these are given in a previous tabulation under iron. An extraction with the DTPA chelate, as was done with iron, is a common method to test for available Zn, Cu, and Mn. The most likely soils to have Zn deficiency are arid lands. Deficiency of Zn is common in beans, corn, grapes, sorghum, citrus, and various deciduous fruits.

Copper is infrequently deficient. Since Cu bonds tightly to certain organic groups, Cu is commonly deficient in certain organic soils (peats or mucks). Crops sensitive to low copper levels include alfalfa, rice, barley, citrus, and rice. *Manganese* is probably as often toxic (in strongly acidic soils) as it is deficient. As with Fe, Zn, and Cu, it is less soluble in high pH (alkaline) soils; Mn deficiency is most common in arid region soils. However, where it has been solubilized and leached out of acidic soils in high rainfall areas, Mn is deficient.

Soil tests for Cu and Mn deficiencies are the DTPA extraction but are in limited use and are somewhat approximate except where good extensive correlation has been done. Crops sensitive to low Mn include alfalfa, citrus, fruits, and potatoes. Specific Mn toxicity has been observed in strongly acidic soils growing cotton (crinkle leaf), tobacco, soybeans, and various fruit trees.

V. Plant Growth, Soil Fertility, and Environmental Pollution

Increases in populations, manufacturing, and luxuriant living coupled with the throw-it-away mentality all help to put stress on our earth, water, and air. Many soil tests are increasingly used (1) to predict those problem pollutants that can affect plant growth and (2) to more accurately predict fertilizer needs as one mechanism to minimize pollution. A well-known saying says, "If it ain't broke, don't fix it." The priority need in environmental pollution is to identify that, indeed, pollution exists. When that is determined, it is then possible to ascertain the identity, concentration, hazard, and source of the pollutant. {*See* SOIL POLLUTION.}

Pollution is defined as the addition of any substance to air, water, or soil which makes that resource less desirable for people's use. Thus, pollution can be substances of undesirable odor or taste, heat, increasing "hardness" (calcium and magnesium) in water, toxins, and many other materials. Pollutants can be many things and are frequently not poisons. Agriculture has been blamed for many pollutants, many of which do also come from urban and city runoff waters and volatile chemicals used by all people. This section will briefly review soil tests and problems associated with (1) the nutrients nitrogen (nitrates) and phosphorus (phosphates), (2) heavy metals, (3) toxic organics other than pesticides, and (4) residual pesticides.

Excess *nitrates* in water can cause the health hazard methemoglobinemia (*blue baby disease* or oxygen deficiency) and the less serious *eutrophication* (growth of algae in nutrient-rich water eventually leading to oxygen-depleted waters). Not only is methemoglobinemia frequently a serious problem to young mammals, but it can also, in high concentrations, cause various levels of brain damage and have other effects to adults. Excess nitrate is reduced to nitrite by microorganisms in the mammal digestive tract. Young mammals lack the stomach acidity to hinder this transformation. The nitrite moves into the blood and oxidizes the oxygen carrier so it cannot carry oxygen to the body. Enough nitrate (about 70% of the oxygen carrier changed) can cause the young mammal to suffocate (= blue baby disease = cyanosis). With less nitrate, various damage, but not death, is possible. Drinking water, and thus drinking water sources (groundwater and surface waters) must not exceed 45 parts per million as nitrate. Eating foods high in nitrate (highly N-fertilized forage or "green" vegetables) may add to the nitrate in the body.

Soil testing for nitrates leaving fields or moving deep into groundwaters is increasing. The tests are simple chemically. The difficulty is in collecting deep samples (several feet below crop roots or from groundwaters) and in being able to identify the surface area from which any measured nitrates originated. A third problem is how to increase N fertilization efficiency to avoid overuse. How does one predict from soil tests the amount of fertilizer nitrogen to add, when it should be added, and how it should be added to minimize excess nitrate loss to waters? This needs to be accomplished without allowing a deficiency for the plant's use nor adding excessively to the costs of application. Research on these problems to determine the best practices for efficient yet adequate fertilizer applications is eagerly in progress.

Other forms of nitrogen are also of concern. Nitrogen oxides (burning of organic wastes and fossil fuels) increase the acidity of rain, aid in depletion of the ozone layer (that protects us from excessive ultraviolet or "tanning" rays), and accentuate some respiratory illnesses. Nitrosamines in many foods are increased by nitrite production and are related to formation of some cancers.

Phosphorus is not a health hazard to people. However, as the most often limiting nutrient in water (it has low solubility), added phosphate is the major cause of *eutrophication*. As the algae grow, die, and are decomposed, the waters' oxygen is lowered. In severe conditions fish and other water life die because of insufficient oxygen. Some have referred to such low-oxygen waters as "dead waters." Many older detergents had a soluble hexametaphosphate as a major portion of its "active" cleaning ingredient. An increase in water's phosphorus can also originate from P adsorbed onto soil particles which are eroded into surface waters.

Soil and water tests are used to ascertain the extent of pollution by nitrates and phosphates. Once the areas and extent of pollution are known, more efficient fertilizer and erosion-control practices can be emphasized as needed. Because phosphorus has low solubility and no volatile forms, the mechanisms to reduce pollution by phosphate can be quite different and are usually less complicated than is reduction of pollution by nitrogen.

Heavy metals are considered a serious health-hazard pollutant. Heavy metals are elements, so they never break down further. Usually they have low solubility and mobility in soils; once they contaminate a soil or lake bed, they move in small amounts and only short distances. There are many metals involved which include cadmium (Cd), mercury (Hg), lead (Pb), chromium (Cr), nickel (Ni), zinc (Zn), copper (Cu), beryllium (Be), selenium (Se), arsenic (As), and many others. Their sources are many: burning fossil fuels, sewage sludges, chemical manufacturing wastes, smelter smoke, electroplating liquid wastes, glazes, putty, paints, and tanning plant liquid wastes.

Soil, water, and plant testing are used to quantify pollutants in soil, water, and foods. Several of these metals (for example Zn and Cu) are plant and animal nutrients and are needed in small amounts, but they are toxic in larger amounts. The plant will take up its nutrients readily but will tend to partially exclude nonnutrients from uptake. Cadmium is one notable exception. Cadmium is readily absorbed and can become a major problem in foods eaten by animals (including people). Monitoring hazardous levels of Cd and other heavy metals is required by law in many states and involves lands on which sewage sludge and some other additives high in hazardous metals are applied.

Various *toxic organics* are common hazards. Excluding pesticides, discussed later in this article, toxic organics include spilled fuels, solvents, spray oils, various materials in sewage sludges, and food processing wastes. The characteristics and variety of these hazards are almost unlimited. Gas, oil, fuel oil, dormant oils, grease solvents, washing detergents, wood preservatives, paint and its wastes, and many other materials can, in particular instances, become hazardous contaminants. The testing for these materials can be complex and require many kinds of instruments and well-trained chemists. [*See* Pest Management, Chemical Control.]

Residual pesticides receive the most scrutiny from those concerned with pollution in agricultural processes. These materials are intended as "pest killers." Many pesticides are harmful also to people. Numerous pesticides are sufficiently hazardous enough that zero measurable levels are allowed in harvested foods. Soil samples and plant tissues are tested for pesticide residues extensively to protect the public against nonpermitted pesticide accumulations. Most analyses are for minute amounts (parts per million parts and parts per billion parts). These residue tests require careful analysis and sensitive gas chromatographs and other expensive equipment for confident and quantitative measurements.

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Soil–Water Relationships

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Glossary

Available water Water in soil between field capacity and permanent wilting point; variable units (e.g., percentage or millimeters of equivalent surface water)

Capillary conductivity Hydraulic conductivity under unsaturated conditions; the term is now considered to be obsolete; same units as for hydraulic conductivity (see Diffusivity)

Darcy's law A law relating the quantity of water flowing through the soil per unit time to the hydraulic gradient; the proportionality constant in the law is the hydraulic conductivity; the Darcy law is needed to solve flow problems in saturated and unsaturated soils

Diffusivity Unsaturated hydraulic conductivity times the rate of change of soil matric potential with water content; units: mm^2/sec

Hydraulic conductivity Proportionality constant in Darcy's law; it is considered to be a constant under saturated conditions, but changes with the moisture content under unsaturated conditions; variable units, but often given as m/sec or m/day

Hydraulic gradient In Darcy's law, the difference in the hydraulic head at two points under consideration in the soil divided by the distance between the points; a reference level must be specified; it is a slope (gradient); units: a length divided by a length

Hydraulic head Elevation (height) with respect to a specified reference level, usually the soil surface, at which water stands in a piezometer in water-saturated soil; the definition of hydraulic head can be extended to soil above the water table, if the piezometer is replaced by a tensiometer; the hydraulic head in either case is the sum of gravitational and pressure potentials; units: a length

Infiltration Entry of water into soil; infiltration rate gives the volume of water entering a specified cross-sectional area of soil per unit time; units of infiltration rate: usually expressed as m/sec or m/day

Nonlimiting water range Range of water that can be absorbed by plant roots, and may be smaller than the available water range; the NLWR acknowledges that both aeration and mechanical resistance affect available water; on one end of the scale, oxygen limits root growth and on the other end of the scale, mechanical resistance restricts root growth; the NLWR becomes narrower as bulk density and aeration limit root growth; same units as for available water

Preferential flow Flow of water in continuous noncapillary-sized voids (e.g., cracks, root channels, worm holes) or in zones of locally high conductivity in capillary-sized pores; in preferential flow, water bypasses the matrix pore space

Sorptivity Measure of the ability of soil to attract water by capillary action; units: $mm/sec^{1/2}$

Tension infiltrometer Instrument that can control preferential flow of water through the macropores and soil cracks; the tension infiltrometer evolved into the disc permeameter, which is used when three-dimensional infiltration is being considered; with these instruments, macropore flow is controlled by applying water to soil at water potentials less than zero

Soil–water relationships can be defined as the interactions between water and the solid and porous parts of the soil. For a typical soil, air and water take up

50% of the space. Organic matter and mineral matter take up the other 50% (Fig. 1). At true saturation, all of the pores are filled with liquid water. At optimum moisture contents for plant growth, the air and water space are about equal, each about 25% of the soil volume. This article will address how the water, solid particles, and pores in the soil are interrelated.

I. Terminology

A. Water Content

Two important expressions used to describe the state of water in the soil are *water content* and *water potential*. The first term gives the amount of water in the soil either by weight or volume and is defined as the water lost from the soil upon drying to constant mass at 105°C. It is expressed either in units of mass of water per unit mass of dry soil (kg/kg) or in units of volume of water per unit bulk volume of soil (m^3/m^3).

B. Water Potential

The second expression utilizies the potential energy status of a small parcel of water in the soil. All water in the soil is subjected to force fields originating from four main factors: the presence of the solid phase (the matrix); the gravitational field; any dissolved salts; and the action of external gas or water pressure. If the force fields in the soil are compared to a reference point, then they can be expressed on a potential energy basis, and each of the four factors can be assigned a separate potential energy value. The sum of these four potential energy values is called the *water potential* of the soil or the *total water potential* to emphasize that it comprises several factors. The reference point for these potential energies is taken as pure free water at some specified height or elevation. Because water is held in the soil by forces of adsorption, absorption, cohesion, and solution, soil water is usually not capable of doing as much work as pure free water. Hence, the water potential is normally negative.

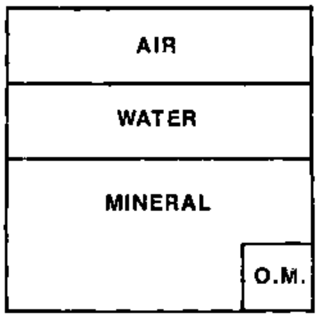

FIGURE 1 Space in a soil. (From Kirkham, D., and Powers, W. L. Copyright © (1972). "Advanced Soil Physics." p. 1. Reprinted by permission of John Wiley and Sons, Inc. Wiley, New York.

1. Matric (Capillary) Potential

The *matric potential energy* or the *matric potential* is the portion of the water potential that can be attributed to the attraction of the soil matrix for water. The matric potential used to be called the *capillary potential*, because, over a large part of its range, the matric potential is due to capillary action akin to the rise of water in small, cylindrical capillary tubes. However, as the water content decreases in a porous material, water that is held in pores due to capillarity becomes negligibly small, when compared to the water held directly on particle surfaces. The term *matric potential*, therefore, covers phenomena beyond those for which a capillary analogy is appropriate.

The matric potential may be determined with a tensiometer, which measures matric potential of water *in situ*. (The word *tensiometer* refers to the fact that it measures the *soil moisture tension*, a term no longer used in defining the components of the water potential. Soil moisture tension has been represented often with a positive sign, in which case it can be considered to be numerically equivalent, but opposite in sign to the matric potential.) The instrument consists of a porous, permeable ceramic cup connected through a water-filled tube to a manometer, vacuum gauge, or other pressure-measuring device. Water pressure in the manometer comes into equilibrium with the adjacent soil through flow across the ceramic cup. The height of the liquid column at this time is an index of matric potential.

The units used to measure matric potential, and other potentials, become evident, when we consider measurement of matric potential with a tensiometer. The force per unit area, or negative pressure of the water in the porous cup, is the weight per unit cross-section of the hanging column. This is the volume of the column divided by the area multiplied by the density of the liquid water and the acceleration of gravity:

$$P = F/A = mg/A = (V)(\rho_w)(g/A) = (hA\rho_w\ g)/A = h\rho_w g, \qquad (1)$$

where P = pressure; F = force; m = mass; g = acceleration due to gravity; A = area; V = volume; ρ_w = density of water; h = height, and the potential (negative pressure) is in units of potential energy or work per unit volume. In the centimeter–gram–second (cgs system of units, 1020 cm of water would exert a negative pressure of

$$(1020\ \text{cm})(1\ \text{g/cm}^3)\ (980\ \text{cm/sec}^2) = 999{,}600\ \text{dyne/cm}^2 \qquad (2)$$

or 1×10^6 dyne/cm^2 = 1 bar, because, in cgs pressure units, 1 bar = 1×10^6 dyne/cm^2. The SI (Système International) unit for pressure is the Pascal, which is 1 Newton per square meter and thus 10 bars = 1 MPa or 1 MegaPascal. The unit (dyne/cm^2) is the same as potential energy/volume, because if we multiply the top and bottom of the fraction, F/A, in Eq. (1) by 1 cm (= cm/cm = unity), we get work/volume = potential energy/volume:

$$[(\text{dyne})(\text{cm})]/[(\text{cm}^2)(\text{cm})] = \text{potential energy/volume} = \text{erg/cm}^3,$$

because 1 dyne-cm = 1 erg.

Units of potential energy per unit volume can be converted to units of potential energy per unit mass by dividing by the density of water, which we shall take to be 1 g/cm^3:

$$(1 \times 10^6\ \text{dyne/cm}^2)/1\ \text{g/cm}^3 = 1 \times 10^6\ \text{dyne-cm/g} = 1 \times 10^6\ \text{erg/g} = 100\ \text{J/kg},$$

because 1 joule = 1×10^7 ergs. Or, 1 bar can be considered to be the equivalent of 100 J/kg. Note that the units of matric potential are not equal to potential energy units (ergs; joules), but can be given in units of potential energy/vol or potential energy/mass.

2. Gravitational Potential

The *gravitational potential energy* or the *gravitational potential* is the potential energy associated with vertical position. The reference height or datum assigned can vary according to need and is often based on utility. It is generally convenient to keep the reference level sufficiently low so that one does not get negative values. Solutions to problems are prone to error when negative numbers are used. Land surveyors take their datum at a level below the lowest level that they expect to encounter on their survey. Then all of their levels will be positive. Soil scientists often take either the soil surface or the groundwater level as the reference level. The reference level usually depends upon the direction of water movement: rising or infiltration. If the reference level is below the point in question, work must be done on the water and the gravity potential is positive; if the level is above, work is done by the water and the gravity potential is negative.

3. Solute Potential

The *solute potential energy* or *solute potential* is the portion of the water potential that can be attributed to the attraction of solutes for water. If one has pure water and solution separated by a membrane, pressure will build up on the solution side of the membrane that is equivalent to the energy difference in water on the two sides of the membrane. This pressure, which is usually called the *osmotic pressure*, is numerically equivalent, but opposite in sign, to the solute potential. The solute potential is often called the *osmotic potential*. The osmotic potential is usually ignored in determining water movement in the soil, unless the soil is saline.

4. Pressure Potential

The *pressure potential energy* or *pressure potential* is the potential energy due to the weight of water at a point under consideration, or to gas pressure which is different from what exists at a reference position. Sometimes this pressure potential energy is divided into two separate components: the *air pressure potential*, which occurs under unsaturated conditions when the soil has an air phase, and the *hydrostatic pressure potential*, which occurs when the soil is saturated and there is a hydrostatic pressure from an overlying water phase. In saturated soil, the pressure potential is sometimes called the *piezometric potential*, because it can be measured with a *piezometer*. A piezometer is a tube placed in soil with its top end open to the atmosphere. It also may have openings in the wall at the point where the pressure measurement is to be taken. The level of water in the tube, measured from a suitable reference, is the piezometer reading. Pressure potentials due to gas may be measured with manometers.

5. Other Potentials Defined

Occasionally, a *tensiometer pressure potential*, which is the potential measured with a tensiometer, is defined. The matric potential differs from the potential measured with a tensiometer, because the soil air pressure is maintained at the reference pressure. The reference pressure can be atmospheric pressure. However, the difference between atmospheric pressure and air pressure in the soil is usually ignored, and the potential measured with a tensiometer is considered to be the matric potential. But if one were comparing measurements of matric potential made with a tensiometer on top of a mountain and at sea level, then one would have to consider air pressure differences.

Other potentials may be defined according to need, such as an *overburden potential*, which occurs when the soil is free to move and some part of its weight becomes involved as a force acting upon water at the point in question. But, when a potential that is not zero is neglected, it must be assumed that it is implicitly included in one of those which is explicit in the definition. For example, when overburden potential is neglected, it becomes implicit in the pressure potential or matric potential.

Water moves in response to differences in water potential. The difference is called the *water potential difference*. The *water potential gradient* is the potential difference per unit distance of flow. Water moves from high potential energy to low potential energy. Under nonsaline, unsaturated conditions, the two most important potentials in the soil are the matric potential and the gravitational potential, and both must be considered in determining the direction of flow of water. Under nonsaline, saturated conditions, the two most important potentials in the soil are the (hydrostatic) pressure potential and the gravitational potential, and the difference in the sum of these two potentials, called the *hydraulic head difference*, governs the soil water flow.

6. Hydraulic Head

The *hydraulic head* is the elevation (height) with respect to a specified reference level, usually the soil surface, at which water stands in a piezometer in water-saturated soil. The definition of hydraulic head can be extended to soil above the water table, if the piezometer is replaced by a tensiometer. The hydraulic head in either case is the sum of gravitational and pressure potentials. For unsaturated soil, the pressure potential is the matric potential with a change in sign as noted earlier. Engineers use the term hydraulic head, because it is easier to use units of length than units of potential energy.

Potential energies as expressed as hydraulic heads are the foundation of engineering practice and are used in studies of tile drainage, irrigation, and transport of water and plant nutrients or pollutants in soil. Potentials are at the basis of all saturated and unsaturated flow problems in which the Darcy law, to be defined, is used.

We can see why units of matric potential energy can be expressed in units of length, or head units, if we look at Eq. (1). In Eq. (1), we note that the values (ρ_w and g) in the last term of Eq. (1) can be considered constant on earth, but not the height, h. Acceleration due to gravity does vary with latitude and elevation, according to Helmert's equation (given in handbooks), but the variation is minor. For example, at Manhattan, Kansas (325 m above sea level; 39° 12′ latitude), we find from Helmert's equation that $g = 979.99$ cm/sec^2, which rounds off to 980 cm/sec^2, the value normally used in solving equations with g. Because g and ρ_w are constant, we can measure matric potential by measuring the height of water in a tensiometer with a ruler. The gravity potential can be measured with a ruler, too, because it is based on the distance above or below a reference point. Therefore, we can get the total head of water under unsaturated conditions (matric potential + gravitational potential) with just a ruler. If the water is under saturated conditions, we can get the total head of water by measuring the height of water in a piezometer with respect to its bottom end and adding this height to the height due to gravity, which is the distance of the bottom end of the piezometer down to the reference level.

II. Static Water

Water is attracted into soil pores predominantly because of the attraction of water to other surfaces (adhesion) and because of capillarity. Surface tension controls the rise or fall of a liquid in a capillary tube. Therefore, we shall now consider surface tension and rise and fall of water in soil pores.

A. Surface Tension

An object is under tension if a pull is being exerted on it. *Tension* is a pull or stretching force per unit area (F/A). The term *surface tension* should not be confused with tension. Surface tension, or more specifically, the *surface tension coefficient*, is an energy per unit area or, equivalently, a force per unit length. But tension is a force per unit area.

Pierre Simon Laplace, the great French mathematician (1749–1827), was the first person to explain mathematically surface tension (1806). A molecule in the body of a fluid is attracted equally from all sides. But a molecule at the surface undergoes a resultant inward pull, because there are no molecules above the liquid causing attraction. Hence, molecules in the surface have a stronger tendency to move to the interior of the liquid than molecules in the interior have to move to the surface. What results is a tendency for any body of liquid to minimize its surface area. This tendency is often opposed by external forces acting on the body of liquid, such as gravity acting on a water drop resting on a flat surface or adhesive forces between water and other materials. Thus, the actual surface may not be an absolute minimum, but rather a minimum depending on the conditions in which the body of liquid is found. Because of surface tension, a thin razor blade or a water beetle can float on the surface of water without breaking through.

B. Water in Capillaries

Surface tension is used to determine the height of rise in capillary tubes. The equation for the height of rise, h_c, of liquid in a capillary tube is:

$$h_c = (2\sigma \cos \alpha)/(r\rho g), \qquad (3)$$

where σ = surface tension (surface tension coefficient) of the liquid (units of g/s^2 or dyne/cm), α = contact angle between the liquid and tube, r = radius of tube (cm), ρ = density of liquid (g/cm^3), and g = acceleration due to gravity (cm/s^2). The equation for the height of rise is derived in standard physics textbooks.

C. Soil Moisture Characteristic Curve

If one keeps track of the moisture withdrawn from an initially saturated soil core, as greater tension is successively applied, and then plots on the x axis (abscissa) water content (moisture percent by volume in the soil) (not the water sucked out) and on the y axis (ordinate), tension head (positive units) or matric potential (negative units), the curve so obtained will be the so-called *moisture characteristic* (ABCD in Fig. 2). The moisture percentage on such a curve may be based on oven-dry weight, but in drainage work, as in the figure, the soil moisture characteristic is most useful when the moisture is expressed on a volume basis, because then the surface centimeters (depth) of irrigation water needed to replenish moisture in the sample is obtained from the characteristic. For example, a moisture percentage of 30% by volume at saturation means that, for a 10-cm dry soil layer, one needs to apply 3 cm of water to the surface to bring the 10 cm to saturation.

D. Falling and Rising Water Table: Hysteresis

In Fig. 2, one may think of the tension as being produced by a falling water table. One may verify the following on the figure: Initially (point A), the bulk volume of the soil has all of its pore space, that is, 50% of its bulk volume, filled with water. For 20 cm depth of water table, the moisture percentage at the soil surface is 40%; for 40 cm depth of water table, 15%; and for 100 cm depth, 8%. In Fig. 2, if the water table had fallen to 40 cm depth and then risen slowly to the soil surface, the moisture percentages would be those corresponding to the dashed line. The failure of the curve to retrace itself in the reverse direction is called *hysteresis*. In Fig. 2, the soil moisture characteristic ABCD is that of a loam. For finer-textured soils, the curves would be higher. If, for Fig. 2, the water table for the dashed curve had not risen slowly, the moisture percentage for zero depth of water table would be, because of trapped air, less than 50%. Even if the water table rises slowly, there is usually a small amount of trapped air, and, when hysteresis loops are determined experimentally, they are not seen to return to the original point.

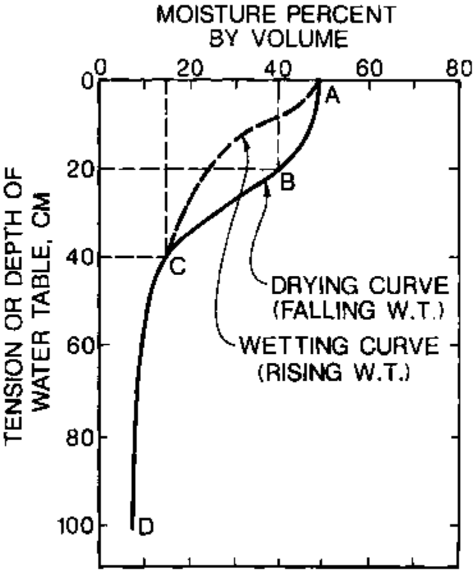

FIGURE 2 A soil moisture characteristic for a loam soil. (From Kirkham, D. (1961). "Lectures on Agricultural Drainage," p. 24. Institute of Land Reclamation, College of Agriculture, Alexandria University, Alexandria, Egypt.

If the soil is saturated to the surface and covered by a thin layer of water, there will be no tension in the soil pores (voids). If the water table falls through the soil surface, tension will develop in the soil pores. If the pores are of the same diameter, they will start to drain and the water level in them will fall the same distance the water table falls. The maximum tension that the falling water table can exert on a soil pore at the soil surface will be $\rho_w gh$ dynes/cm^2, where h is the depth of the water table below the soil surface. If the diameter of the pore is too large to support this tension, the pore will not be subject to the maximum tension.

However, pores in the soil are not the same diameter. Figure 3 illustrates what happens in a soil pore of variable diameter, when the water table falls for six different cases of water table fall. The depth of soil and the length of the pore channel for each case is taken as 15 cm, so that, for the heights of capillary rise shown, the diameter of tube nearest the surface is calculated to be 0.075. Thus, the scale in the horizontal direction is, as seen in the figure (2/0.075 =), 27-fold that of the vertical direction. In part A of the figure, the soil is shown saturated to the surface. In parts B, C, D, E, and F, the water table is shown at successively greater depths. In part B, 4 cm height of water column is held; in part C, also 4 cm. In part D only sufficient water curvature has developed in the narrow neck to support about 5 cm height of water. In part E additional curvature has developed in the narrow neck, such that about 8 cm height of water is supported. In part E the water table is at 13 cm depth and in part F it is at 15 cm depth, a drop of 2 cm. In dropping these 2 cm, the ability of the narrow neck to support the needed 2 cm is exceeded and the pore then empties suddenly and discontinuously to about the level of the water table. This example shows that the emptying of individual pores occurs discontinuously. When the water is removed from a large number of pores, as for any soil sample, a graph of moisture percentage versus tension (or matric potential) does not show the discontinuous nature of the pore-emptying process. The example also shows that soil pores can be filled with water (saturated), yet the water is under tension in the pores.

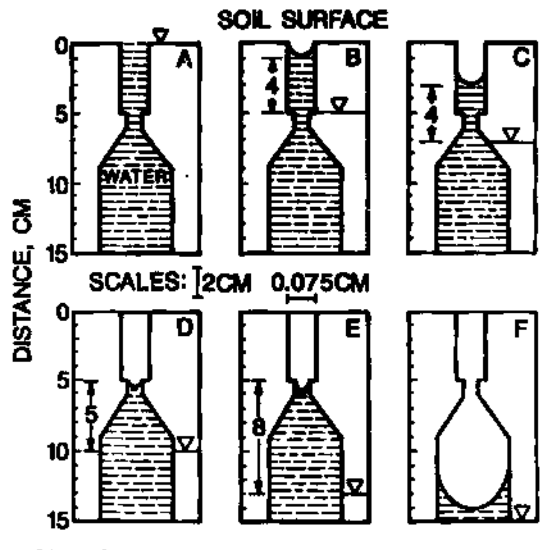

FIGURE 3 The falling water table in a soil pore (channel) of variable diameter. Note the difference in the vertical and horizontal scales. The water table is indicated by an inverted Greek "delta." (From Kirkham, D. (1961). "Lectures on Agricultural Drainage." p. 27. Institute of Land Reclamation, College of Agriculture, Alexandria University, Alexandria, Egypt.

In Fig. 4, at the left, three shapes of pores are shown when the water table has fallen from a level A to the level B. The same three pores are shown at the right when the water table has risen from a level C (say) to the level B. At the left, the pores are filled up to the height h_c, the capillary height of rise. At the right, only one pore is filled up to the height h_c; one pore is empty; and one is partially filled. The soil at the left, for the water table falling, has a much higher moisture percentage than the soil at the right for the water table rising.

Figure 4 also gives a physical picture for hysteresis shown in Fig. 2. A soil that is being wet up from a rising water table holds less water than a soil that is being dried down. For the falling water table, water is held in tubes of supercapillary size, if there is a restriction of capillary size at or below the height of capillary lift. Water can be drawn up above a water table, however, only by a continuous capillary opening without supercapillary enlargements. Hence, more water is held in the *capillary fringe*, which is the thickness of saturated water held by capillarity above the water table, above a sinking water table than above a rising water table. These concepts were explained in 1937 by Cyrus Fisher Tolman of Stanford University in his classic book, *Ground Water*.

One concludes from Fig. 4 that applications of subirrigation water to raise the water table will not result in the same amount of moisture in the capillary fringe as will applications of surface water. Subirrigation would provide more soil aeration than surface addition of water. This may be desirable in some cases.

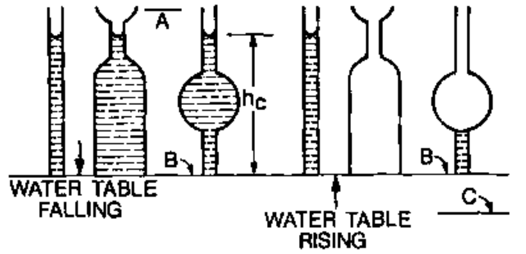

FIGURE 4 Soil pore conditions for a falling and for a rising water table. (From Kirkham, D. (1961). "Lectures on Agricultural Drainage," p. 28. Institute of Land Reclamation, College of Agriculture, Alexandria University, Alexandria, Egypt.

III. Dynamic Water

A. Saturated Soil

1. Darcy's Law

Understanding movement of water in saturated soil is important in drainage and groundwater studies. The French hydraulic engineer, Henry Philibert Gaspard Darcy (1803–1858) determined experimentally the law that governs the flow of water through saturated soil (1856). It is called *Darcy's law* and to illustrate it, let us consider Fig. 5, which shows water flowing through a soil column of length L and cross-sectional area, A.

The law can be stated as follows:

$$Q = -KA(h_2 - h_1)/(z_2 - z_1), \qquad (4)$$

where Q is the quantity of water per second such as in cubic centimeters per second, often called the *flux*; K, centimeters per second, is the *hydraulic conductivity* (the law defines K); heads h_1 and h_2 and distances z_1 and z_2 are as shown in Fig. 5. The reference level here is the x, y plane. The head h_1 is the hydraulic head for all points at the bottom of the soil column, that is, at $z = z_1$, and similarly the head h_2 applies to all points at the top of the soil column, $z = z_2$. The length of the column is $z_2 - z_1 = L$. The negative sign in the Darcy equation is used so that a positive value of Q will indicate flow in the positive z direction. The positive z direction is measured from z_1 to z_2. In the Darcy law equation, the quantity $(h_2 - h_1)/(z_2 - z_1)$ is called the *hydraulic gradient i*; the ratio Q/A is called the flux per unit cross-section or *flux density* $(\mathrm{cm^3/sec})/\mathrm{cm^2}$. The ratio Q/A is also called the *Darcy velocity v* or, very often, just the *velocity v*. Therefore, Darcy's law may be written as $v = -Ki$. The *actual velocity* of the water in the soil is much greater than the Darcy velocity. The actual velocity is on the average v/f, where f is the *porosity* or the *wetted porosity* to emphasize that there is no air in the pores. The porosity is the volume of pores in a soil sample divided by the bulk volume of the sample. The pores can be filled with air and/or water. The percentage porosity in the soil can be determined from the following equation:

$$\%\ \text{porosity} = 100\% - (\text{bulk density}/\text{particle density}) \times 100. \qquad (5)$$

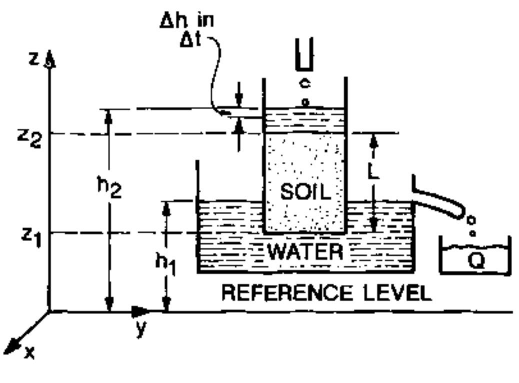

FIGURE 5 Illustration of Darcy's law. (From Kirkham, D., and Powers, W. L. Copyright © (1972). "Advanced Soil Physics," p. 47. Wiley, New York. Reprinted by permission of John Wiley and Sons, Inc.

The Darcy velocity v means more than flux per unit area Q/A. In Fig. 5, suppose that the supply of water shown dripping into the soil column is abruptly cut off during a short time interval Δt during which h_2 decreases by Δh. We let Δq be the volume of water flowing downward through the soil in Δt. Because Q is the flow per second, we may write Δq as $\Delta q = Q\Delta t$, and we also have by continuity of flow $\Delta q = A\Delta h$. Therefore, $Q\Delta t = A\Delta h$, and $Q/A = \Delta h/\Delta t$. Physically, $\Delta h/\Delta t$ is a velocity; therefore, so is $v = Q/A$. Thus, the Darcy velocity v represents the rate $\Delta h/\Delta t$ approaches dh/dt of fall of surface water in Fig. 5. If the hydraulic gradient is unity (pressure potential same at top and bottom of soil column), then $v = -K$. Thus, it is determined that K is numerically equal to the rate of fall of a thin layer of ponded water into the soil, under only the force of the earth's gravitational pull. We also see that K is the velocity under a unit hydraulic gradient.

Flow in a vertical soil column has been used to derive and illustrate Darcy's law. However, the law and principles developed above apply for flow of water in any direction in the soil.

2. Hydraulic Conductivity

The hydraulic conductivity should not be confused with the *intrinsic permeability*, sometimes just called the *permeability*, of the flow medium. The intrinsic permeability can be used to denote the permeability of the medium without reference to the fluid that is moving. The intrinsic permeability, symbolized by k by M. Muskat, a petroleum engineer in the United States well known for his studies in the 1930s and 1940s of fluid flow through porous media, is equal to $K\eta/\rho g$, where K is the Darcy hydraulic conductivity, η is the fluid viscosity, ρ is the fluid density, and g is the acceleration due to gravity. Dimensionally, k is an area (L^2). The units of K are m/day, which is the same as (m^3/m^2)/day. That is, K may be interpreted as the m^3 of water seeping through a m^2 of soil per day under a unit hydraulic gradient.

Hydraulic conductivity in natural field soil is governed by factors such as cracks, root holes, worm holes, and stability of soil crumbs. Texture, that is, the percentage of the primary particles of sand, silt, and clay, usually has a minor effect on hydraulic conductivity, except for disturbed soil materials. The hydraulic conductivity of natural soils in place varies from about 30 m/day for a silty clay loam to 0.05 m/day for a clay. The hydraulic conductivity for disturbed soil materials varies from about 600 m/day for gravel to 0.02 m/day for silt and clay. The value of K can be made higher or lower by soil management. Roots of crops after decay increase K; compaction of soil by animals or machinery decreases K, at least in the surface soil.

Ordinarily one considers K in $v = -Ki$ to be a constant under saturated flow. It is a constant if (a) the physical condition of the soil and of the water does not change in space or time as the water moves through the soil (e.g., the soil is *isotropic*, that is hydraulic conductivity is the same regardless of the direction of measurement) and if (b) the type of flow is laminar, that is, not turbulent. In laminar flow, two particles of water seeping through the soil will describe paths (streamlines) that never cross each other. In turbulent flow, eddies and whirls develop. The possibility of turbulent flow is considered in soil only if the soil is a coarse sand or gravel, and then only if the hydraulic gradients are large (larger than found in most problems of interest to agricultural soil scientists).

3. Laplace's Equation

To solve groundwater seepage and drainage problems, it is desirable to have a general differential equation. It is found that Laplace's equation applies, which is a familiar equation occurring in nearly all branches of applied mathematics. Laplace's equation is derived from Darcy's law and the *equation of continuity*. The equation of continuity states mathematically that mass can be neither created nor destroyed. We can state the equation of continuity in words, as follows: For a volume element x times y times z, the change in velocity of water in the x direction plus change in velocity of water in the y direction plus change in velocity of water in the z direction is equal to the total change in water content, Θ, per unit time of the volume element under consideration. That is, inflow of water in the element minus outflow of water is equal to the water accumulated. Let us imagine a rectangular x, y, z system of coordinates that is established in a homogeneous porous medium of constant hydraulic conductivity, and let h be the hydraulic head referred to an arbitrary reference level for a point (x,y,z) and let time be t and v_x, v_y, and v_z be the velocity of water flowing in the x, y, and z directions, respectively; then, with Θ being the volume of water per unit volume of bulk soil, from the equation of continuity,

$$-\ [(\partial v_x/\partial x) + (\partial v_y/\partial y) + (\partial v_z/\partial z) = \partial\Theta/\partial t \quad (6)$$

and Darcy's law, one may, for incompressible steady-state $(\partial\theta/\delta t = 0)$ flow in a porous medium where K is constant, derive the expression

$$(\partial^2 h/\partial x^2) + (\partial^2 h/\partial y^2) + (\partial^2 h/\partial z^2) = 0, \quad (7)$$

as the expression governing groundwater flow. The steady, saturated-flow equation is abbreviated $\nabla^2 h = 0$.

Charles S. Slichter, a mathematician at the University of Wisconsin, was the first to show in 1899 that Laplace's equation applies to the motion of groundwater. Many mathematical solutions for groundwater flow using Laplace's equation have been done by Don Kirkham of Iowa State University.

B. Unsaturated Soil: Diffusivity

So far, we have been considering water flow in saturated soils. Although flow in saturated soils is important, soils are not generally water saturated (saturated meaning that the matric potential is equal to zero).

We now consider concepts of unsaturated flow. Using the equation of continuity and assuming that Darcy's law holds for unsaturated moisture flow, one may derive the following equation:

$$(\partial/\partial x)k(\partial h/\partial x) + (\partial/\partial y)k(\partial h/\partial y) + (\partial/\partial z)k(\partial h/\partial z) = \partial\Theta/\partial t, \quad (8)$$

where k is hydraulic conductivity under unsaturated conditions, h is the hydraulic head, and Θ is the fraction of the soil bulk volume occupied by water. If the soil is saturated, the equation reduces to Laplace's equation because k and Θ become constants. In the past, k has been called the *capillary conductivity*, but the term is now considered to be obsolete by the Soil Science Society of America, because a capillary model may not apply to the movement of water under unsaturated conditions. For solutions of Eq. (8), the result has depended upon three factors:

1. We replace h, the hydraulic head, by

$$h = \Psi + z, \qquad (9)$$

where Ψ is the called the matric potential or capillary potential (rather than the pressure potential, because the soil is now not saturated) and z is the gravitational head, as before. In 1931, L. A. Richards a (then) doctoral student at Cornell University in New York published the equation in which h is replaced by Ψ and z:

$$(\partial/\partial x)k(\partial\Psi/\partial x) + (\partial/\partial y)k(\partial\Psi/\partial y) + (\partial/\partial z)k(\partial\Psi/\partial z) + \partial k/\partial z = \partial\Theta/\partial t. \qquad (10)$$

Equation (10) is known as Richards's equation, a nonlinear, partial differential equation. Such equations are difficult to solve. In 1955, John R. Philip of Australia gave a solution.

2. We introduce a term called the *diffusivity* D, defined by

$$D = k(\partial\Psi/\partial\Theta). \qquad (11)$$

D has units of [mm^2/sec]. In 1936, Ernest C. Childs in England noted that, under unsaturated conditions, water moves according to diffusion equations.

3. We now make use of a mathematical transformation, so-called the *Boltzmann transformation*, which involves the time t to the one-half power. In 1952, Arnold Klute a doctoral student at Cornell University in New York introduced this Boltzmann variable:

$$\lambda = 1/2\ xt^{-1/2}. \qquad (12)$$

He wrote the flow equation in a diffusion form with water content, Θ, as the dependent variable:

$$\partial\Theta/\partial t = (\partial/\partial z)D(\partial\Theta/\partial z) + (\partial k/\partial z). \qquad (13)$$

He then restricted himself to the gravity-free case (horizontal flow into a soil column):

$$\partial\Theta/\partial t = (\partial/\partial x)D(\partial\Theta/\partial x). \qquad (14)$$

Klute transformed the partial differential equation into an ordinary differential equation by using this Boltzmann variable.

In 1907, Edgar Buckingham of the USDA Bureau of Soils in Washington, DC already had published a bulletin entitled "Studies on the Movement of Soil Moisture," which established the mathematics of unsaturated soil water flow. He saw that the capillary conductivity (the unsaturated hydraulic conductivity) is a function of water content or matric (capillary) potential. The flow equation is sometimes known as the *Darcy-Buckingham law*, which honors both its discoverers in the saturated and unsaturated realms.

Thus, description of water flow in soil requires the functions $D(\Theta)$ and $k(\Theta)$. In general, it is difficult to measure $D(\Theta)$, especially *in situ*. It is simpler to measure the total effect of the capillary attractiveness of soil, namely the *sorptivity* S [mm/sec$^{1/2}$], a term defined by Philip in 1969. The sorptivity is equal to the following:

$$S = {}_{\Theta_n}\!\int^{\Theta_s} \lambda\, d\Theta \qquad (15)$$

and can be approximated by the following equation:

$$S_o^2 = [(\Theta_o - \Theta_n)/b]\,{}_{\Theta_n}\!\int^{\Theta_o} D\, d\Theta \qquad (16)$$

where Θ_n is the initial soil water content, Θ_s is the saturated water content, Θ_o is the water content to which the soil surface is wet, and $\frac{1}{2} < b < \pi/4$, often $b \cong 0.55$. Thus, to interpret S_o, in terms of D, requires measurement of Θ_n and Θ_o, which can be easily determined. In theory, to describe flow in a uniform soil, one only requires instruments to measure the sorptivity and the conductivity function from saturation, Θ_s, where $\Theta_o = \Theta_s$, which is at the free water condition of $\Psi_o = 0$, down to $\Theta = \Theta_n$ and $\Psi = \Psi_n$, where commonly $\Psi_n \rightarrow -\infty$.

IV. Infiltration

Infiltration rate may be defined as the meters per unit time of water entering into the soil regardless of the types or values of forces or gradients. The term hydraulic conductivity, which has been defined as the meters per day of water seeping into the soil under the pull of gravity or under a unit hydraulic gradient, should not be confused with infiltration rate. Infiltration rate need not refer to saturated conditions. If two rain drops of total volume 2 mm^3 = 0.000002 m^3 fall per day on a m^2 of soil and are absorbed into the soil, the infiltration rate is 0.000002 m/day.

Water entry into soil is caused by matric and gravitational forces. Therefore, this entry may occur in the lateral and upward directions, as well as the downward one. Infiltration normally refers to the downward movement. The matric force usually predominates over the gravitational force during the early stages of water entry into soil, so that observations made during the early stages of infiltration are valid when considering the absence of gravity.

If water infiltrates into a dry soil, a definite *wetting front*, also called a *wet front*, can be observed. This is the boundary between the wetted upper part of the soil and the dry lower part of the soil. If water is infiltrating into soil contained in a clear plastic column, one can observe the progress of the wet front and mark wet fronts as they change with time (Fig. 6). At present, it is impossible to measure the matric potential exactly at the wet front, because it progresses too rapidly into the soil. However, one can measure amount of water infiltrated and the depth and shape of the wet front, and come to important conclusions about the entry of water into the soil. Infiltration is extremely important, because it determines not only the amount of water that will enter a soil, but also the entrainment of the "passenger" chemicals (nutrients, pollutants) dissolved in it.

Four models for infiltration into the soil have been developed. They all deal with one-dimensional, downward infiltration into the soil.

A. Lewis Equation

From work initiated in 1926, Mortimer Reed Lewis, an irrigation engineer at Oregon State College, used the following equation for infiltration:

$$I = \gamma t^{a}, \tag{17}$$

where I is the cumulative infiltration between time zero and t, and γ and a are constants. Equation (17) has been erroneously attributed to A. N. Kostiakov, and often appears in the literature as the "Kostiakov" equation. The parameters in Eq. (17) are evaluated by fitting the model to experimental data. By definition, the infiltration rate $i = dI/dt$. Thus, the infiltration rate for the Lewis equation is given by

$$i = a\gamma t^{a-1}. \tag{18}$$

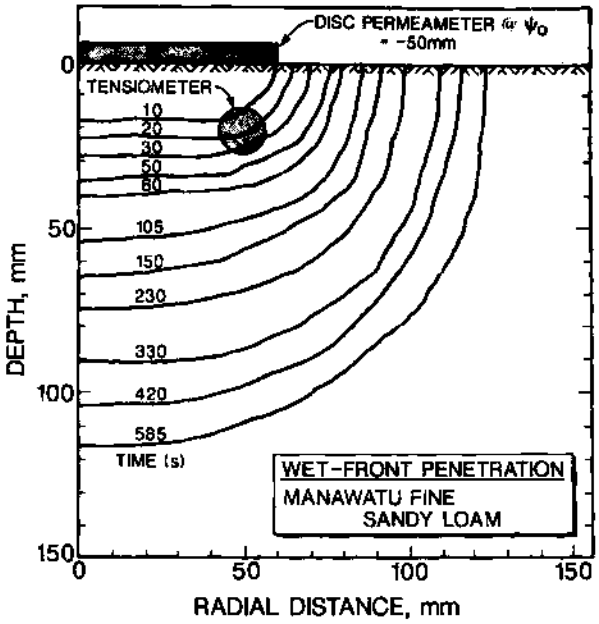

FIGURE 6 Wet fronts for a sandy loam soil. (From Kirkham, M. B., and Clothier, B. E. (1994). Ellipsoidal description of water flow into soil from a surface disc. *Trans. Int. Congr. Soil Sci.* **15**, in press.)

B. Horton Equation

In the 1930s, Robert E. Horton, a pioneer in the study of infiltration in the field, developed the following equation:

$$i = i_f + (i_0 - i_f)\exp(-\beta t). \tag{19}$$

where i_0 is the initial infiltration rate at $t = 0$, i_f is the final constant infiltration rate that is achieved at large times, and β is a soil parameter that describes the rate of decrease of infiltration.

Horton felt that the reduction in infiltration rate with time was largely controlled by factors operating at the soil surface. These included swelling of soil colloids and the closing of small cracks, which progressively sealed the soil surface. He also recognized that a bare soil surface was compacted by raindrops, but crop cover mitigated their effect. Horton's field data showed that the infiltration rate eventually approached a constant value, which was often somewhat smaller than the saturated permeability of the soil. The latter observation was thought to be due to air entrapment.

C. Green and Ampt Equation

The above models are empirical. W. Heber Green and G. A. Ampt in Australia published in 1911 an infiltration equation that was based upon a simple physical model of the soil. It has the advantage that the parameters in the equation can be related to physical properties of the soil. Physically, Green and Ampt assumed that the soil was saturated behind the wetting front and that one could define some "effective" matric potential at the wetting front. During infiltration, if the soil surface is held at a constant matric potential or head h_0 with associated water content Θ_0 (e.g., by ponding water over it), water enters the soil behind a sharply defined wet front that moves downward with time (Fig. 7a). Green and Ampt replaced this process with one that has a discontinuous change in water content at the wetting front (Fig. 7b). In addition, they made the following assumptions: (i) The

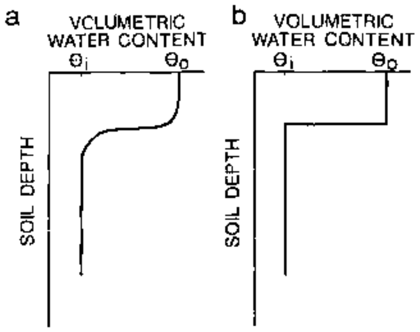

FIGURE 7 Water content profiles during infiltration. (a) A profile that actually occurs during infiltration. (b) A profile corresponding to the Green-Ampt infiltration model. (From Jury, W. A., Gardner, W. R., and Gardner, W. H. Copyright © (1991). "Soil Physics," 5th ed., p. 132. Wiley, New York. Reprinted with permission of John Wiley and Sons, Inc.)

soil in the wetted region has constant properties (K_o, Θ_o, D_o, h_o, where K_o and D_o are the hydraulic conductivity and water diffusivity in the Green-Ampt model, respectively) and (ii) the matric potential (head) at the moving front is constant and equal to h_F.

The Green-Ampt model can be used to calculate the infiltration rate into a horizontal soil column initially at a uniform water content Θ_i such that $\Theta_o > \Theta_i$ and an associated matric potential or head h_o maintained at the entry surface for all times > 0. Using the assumptions of the model and Darcy's law, the following equation can be derived:

$$i = (dI/dt) = \Delta\Theta(D_o/2t)^{1/2}, \tag{20}$$

where i = infiltration rate, t = time, $\Delta\Theta = \Theta_o - \Theta_i > 0$, $D_o = K_o\Delta h/\Delta\Theta$ is the soil water diffusivity of the wet soil region $0 < x < L$, the depth of the wetting front, and $\Delta h = h_o - h_F > 0$, and K_o is the constant hydraulic conductivity of the wet region, and h_F is the matric potential or head of the moving front. Note in this model that the infiltration rate into the soil is proportional to $t^{-1/2}$. A similar expression is obtained for infiltration into a vertical soil column at short times after infiltration begins.

The model has been used as a conceptual aid in visualizing a complex process. Indirect evaluation of h_F has permitted the model to be used in practical applications.

D. Philip Infiltration Model

J. R. Philip in 1957 suggested an approximate algebraic equation (based on sound physical reasoning) for vertical infiltration under ponded conditions. The equation, which is simple yet physically well founded, is as follows:

$$I = St^{1/2} + At, \tag{21}$$

where I is the cumulative infiltration (mm), S is the sorptivity (mm hr$^{-1/2}$), and A is an empirical constant (mm/hr). The first term on the right-hand side of Eq. (21) gives the gravity-free absorption into a ponded soil due to capillarity and adsorption. The second term represents the infiltration due to the downward force of gravity. S and A may be found empirically by fitting Eq. (21) to infiltration data. Alternatively, these parameters may be derived from the hydraulic properties of the soil. This is not possible for other empirical infiltration equations. For horizontal infiltration, cumulative infiltration I is given by

$$I = St^{1/2}. \tag{22}$$

E. Two- and Three-Dimensional Infiltration

The previous discussion dealt with one-dimensional infiltration in which water is assumed to flow vertically (or more rarely horizontally) into the soil. Multidimensional infiltration theory is an area of soil physics research dominated by the works of J. R. Philip, who published his first paper on the topic in 1966. Sequels to his work have been carried out by Peter A. C. Raats (1971) in the Netherlands and Robin A. Wooding (1968) in New Zealand.

Multidimensional infiltration models have utilized difficult mathematics. However, practical advances in infiltration can be made with simple models. For example, recently, a simple, ellipsoidal description of the pattern of wetting to approximate the depth to the wetting front underneath a disc permeameter, set at Ψ_o and supplying water to soil initially at water content Θ_n, has been described. Wet fronts shown in Fig. 6 were used in developing such an ellipsoidal model.

F. Redistribution

The term redistribution refers to the continued movement of water through a soil profile after irrigation or rainfall has stopped at the soil surface. Redistribution occurs after infiltration and is complex, because the lower part of the profile ahead of the wet front will increase its water content, and the upper part of the profile near the surface will decrease its water content, after infiltration ceases. Thus, hysteresis can have an effect on the overall shape of the water content profile.

V. Preferential Flow

The water flow equations have been derived using the assumption that the soil has a continuous solid matrix, which holds water in pores and films. Field soil, however, has a number of interconnected cracks, root holes, worm channels, and other voids, whose physical properties differ from the surrounding soil matrix. If filled, these continuing flow channels have the capacity to carry large amounts of water at velocities that greatly exceed those in the surrounding matrix. We first define and then consider the characteristics of these voids.

A. Microporosity and Macroporosity

Pores have been classified into different sizes, as follows:

Macropores: diameters ranging from >5000 to 75 μm;
Mesopores: diameters ranging from 30 to 75 μm;
Micropores: diameters ranging from 5 to 30 μm.

It is often more important to characterize soil pores in terms of their function, in particular with regard to their ability to store and conduct water, rather than their diameter. Transport through soil of water with its dissolved chemicals, as well as gaseous exchange, depends critically upon soil pores, and especially upon the continuous and connected macropores.

Functionally, we can distinguish between *macroporosity* and *matrix porosity*. Macroporosity refers to the interconnected pore space of voids, which causes preferential transport of both water and chemicals. When transport occurs through the macropores, there is limited exchange of water between the macropores and the pores of the matrix. Matrix porosity refers to those pores in which the flow through the body of the soil is slow enough so that there is extensive interpore mixing.

If we consider the unit soil pore to be a cylinder of radius r, then the Hagen-Poiseuille law can be used to describe the flow through the pore:

$$q = -(r^2/8\eta)(\Delta P/\Delta x), \qquad (23)$$

where q is the flux density (m/sec), η is the viscosity of water (kg m^{-1} sec^{-1}), and ΔP (Pa) is the pressure difference across the small pipe (pore) of length Δx. Since the flux density increases with the square of the radius, the macropores can have a great impact on soil-transport processes. This is especially true because the macropores frequently form an interconnected network. However, they are fragile and can easily be disrupted, particularly at the soil surface where they can be rendered ineffective by sealing. Much of the biologically created macroporosity drops off with depth as the populations of soil flora and fauna decline.

B. Macroporosity and Hydraulic Conductivity

Because of macroporosity, the hydraulic conductivity function, $K(\Psi)$ can vary dramatically, mainly as a result of changes in the characteristics of the larger, surface pores that become filled only at high potentials near saturation. Figure 8 shows how the hydraulic conductivity function varies with soil management. At the wet end, the role of macropores is paramount in determining $K(\Psi)$. Here management (e.g., plowing) or natural events (e.g., crusting of the soil after rainfall) can modify rapidly the hydraulic conductivity by altering surface-venting and subsurface connectedness. The upper curve in Fig. 8 shows a soil with macropores, and the lower line shows a soil controlled by matrix flow.

Tillage, especially, affects pore size. Pores are smaller in tilled soils, because tillage pulverizes the soil. When the soil is not tilled, decaying roots and other organic matter create voids. Also earthworms thrive on the organic matter and their populations are greater in soil that has not been tilled. Earthworm holes and root channels are a prime reason for the difference in hydraulic conductivity between cultivated and no-till soil.

C. Tension Infiltrometers

Recognition of the importance of macropores and preferential flow has led to the development of instruments that can be used in the field to control preferential water flow through macropores and soil cracks. The first practical instrument was developed in 1981 by Brent E. Clothier of New Zealand and Ian White of Australia. This simple instrument was known as the *sorptivity tube* or more latterly as the *tension infiltrometer*. Later still it has evolved into the *disc permeameter*, as described by Keith M. Perroux and I. White in 1988. The disc permeameter is used when three-dimensional infiltration is being considered. With these instruments, the amount of macropore flow measured is controlled by applying water to soil at

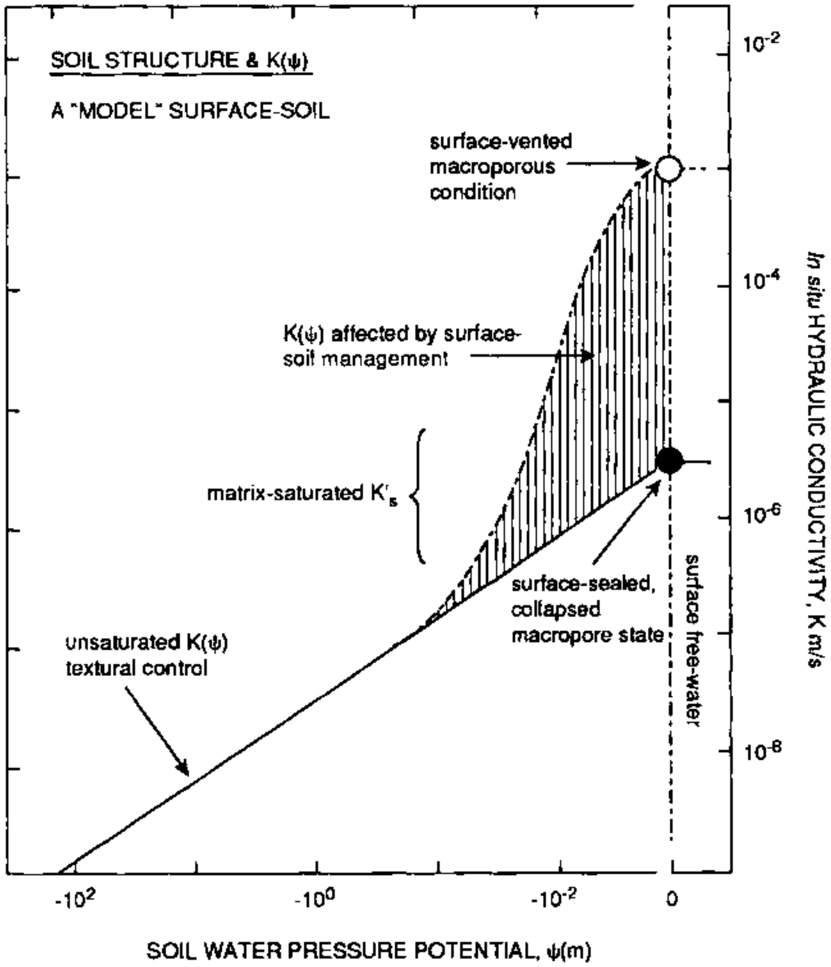

FIGURE 8 A hydraulic conductivity function, $K(\Psi)$. The shaded area identifies the modification that soil management might impart upon the hydraulic conductivity. Also identified by a solid dot is the saturated hydraulic conductivity of the matrix (K_s), i.e., the soil minus those macropores that drain when Ψ_0 is less than about −30 mm. (From Clothier, B. E. (1990). Root zone processes and water quality: The impact of management. *In* "Proceedings of the International Symposium on Water Quality Modeling of Agricultural Nonpoint Sources. Logan, Utah, June, 1988." (D. G. DeCoursey, ed.) pp. 659–683. United States Department of Agriculture, Agricultural Research Service, Report No. ARS-81, p. 671.)

water potentials, Ψ_0, less than 0. The maximum diameter of vertical pores, connected to the soil surface, through which water can enter is given by the capillary rise equation (Eq. (3)) and is proportional to the matric potential, $(-\Psi_0)^{-1}$. The more negative Ψ_0, the smaller is the maximum diameter of a pore that can participate in flow from the soil surface. These two instruments are being used to supply water to soil *in situ* at readily selectable, zero or negative pressures. A "ready reckoner" of the relationship between the negative pressure Ψ, where Ψ is in terms of energy per unit weight (in cm of H_2O head), and the capillary diameter d in mm is $-3/d$.

Many water flow processes of interest such as groundwater recharge are concerned only with area-averaged water input. Therefore, preferential flow of water through structural voids does not necessarily invalidate equations that assume homogeneous flow. However, preferential flow is of critical importance in solute transport, because it enhances chemical mobility and can increase pollution hazards.

VI. Soil Water in Relation to Plants

A. Soil Water Budget

The amount of water available for plant uptake has been related to a soil's *water budget*. The three terms associated with the water budget are *wilting point*

(W.P.), *field capacity* (F.C.), and *available water* (A.W.).

1. Field Capacity

To define field capacity we consider the following. In many soils, after a rain or irrigation, the soil will immediately start draining to the deeper depths. After 1 or 2 days the water content in the soil will reach, with time, for many soils, a nearly constant value for a particular depth in question. This somewhat arbitrary value of water content, expressed as a percentage, is called the field capacity. Field capacity is often estimated to be the water content at a soil matric potential of about −0.03 MPa. The field capacity might be measured as 5% of water per unit volume of bulk soil for a sand, which we shall label A, and might be measured as 50% per unit volume of bulk soil for a heavy clay, which we shall call B.

2. Wilting Point

The wilting point, also called the *permanent wilting point*, may be defined as the amount of water per unit weight or per unit soil bulk volume in the soil, expressed in percent, that is held so tightly by the soil matrix that roots cannot absorb this water and a plant will wilt. The wilting point is usually estimated to be the water content at a soil matric potential of −1.5 MPa. The wilting point might be 2% water per unit volume for the sand A, and it might be 20% per unit volume for the heavy clay B.

3. Available Water

Plant available water, $A.W.$, may be defined as the difference between field capacity, $F.C.$, and wilting point, $W.P.$ The formula is

$$A.W. = F.C. - W.P. \tag{24}$$

Using the numerical values of $W.P.$ and $F.C.$ for the sand A and heavy clay B, we find available water as

(Sand A) $A.W. = 5\% - 2\% = 3\%$
(Heavy clay B) $A.W. = 50\% - 20\% = 30\%$.

The above two $A.W.$'s are in percentages referred to a volume of bulk soil. These $A.W.$'s may be considered to mean that, in 100 cm of the sand A profile, there are 3 cm of equivalent surface water in the plant available form; and in 100 cm of heavy clay B, there are 30 cm of equivalent surface water in plant available form. The clay soil B stores (30 − 3) = 27 cm more of equivalent surface water per meter depth of soil profile than does the sand A. From this example, we see that soil texture can have a large effect on soil water availability.

The terms should be used with caution. They do not apply to certain exceptional soils. The terms should be based on moisture measurements made in the field to a depth of interest, say 100 to 150 cm, not on laboratory measurements. Field capacity is of doubtful value for soils having water tables or layers of widely differing hydraulic conductivity. Some have questioned the use of "field capacity" at all, because the soil water is not static and is always moving, even if the movement is small. In the 1970s, the Soil Science Society of America (SSSA) considered the term obsolete in technical work. However, in recent years, the SSSA has recognized its utility in practical field work, and the term is no longer considered obsolete.

Equation (24) implies to some agronomists that water can be taken up by plant roots with equal ease, from field capacity to the wilting point. This view was promulgated by F. J. Veihmeyer and A. H. Hendrickson at the University of California in Davis, who collaborated for many years starting in the 1920s. For most crops, however, yields are reduced if the water in the soil approaches the wilting point before water is supplied.

4. Nonlimiting Water Range

In 1985, John Letey, a soil physicist at the University of California in Riverside, developed a concept called the *nonlimiting water range* (NLWR), which acknowledges that water may not be equally available to plants between field capacity and the permanent wilting point. The interaction between water and other physical factors that affect plant growth must be considered. Bulk density and pore size distribution affect the relationship between water and both aeration and mechanical resistance. The relationship between water and aeration is opposite to that between water and mechanical resistance. Increasing water content decreases aeration, which is undesirable, but decreases mechanical resistance, which is desirable. The nonlimiting water range may be affected by aeration and/or mechanical resistance (Fig. 9). The NLWR becomes narrower as bulk density and aeration limit plant growth. On one end of the scale, oxygen limits root growth and on the other end of the scale, mechanical resistance restricts root growth. The restriction may occur at a water content higher than the value that would be considered limiting to plants on the basis of plant available water.

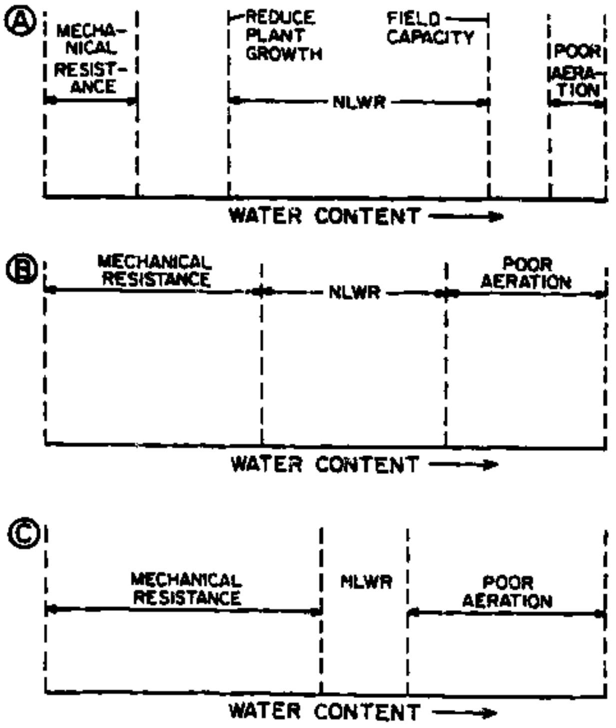

FIGURE 9 Generalized relationships between soil water content and restricting factors for plant growth in soils with increasing bulk density and decreasing structure in going from case A to C. The nonlimiting water range is abbreviated NLWR. (From Letey, J. (1985). Relationship between soil physical properties and crop production. *Adv. Soil Sci.* **1**, 277–294.)

B. Drought and Flooding

Plant water status is primarily described by the same two basic parameters that describe soil water: the water content (Θ) and the energy status of the water, usually expressed as the total water potential or water potential, Ψ. As for soils, under equilibrium conditions, the state of water at a particular point in a plant may be written in terms of the various components of the potential energy, as follows:

$$\Psi = \Psi_s + \Psi_p + \Psi_m + \Psi_g, \qquad (25)$$

where Ψ is the water potential, Ψ_s is the osmotic (solute) – potential component, Ψ_p is the pressure (turgor) – potential component, Ψ_m is the matric component due to capillary or adsorption forces such as those in the cell wall, and Ψ_g is the component due to gravity. For plants, the matric potential and the gravitational potential are usually neglected, and Eq. (25) reduces to

$$\Psi = \Psi_s + \Psi_p. \qquad (26)$$

Wherever plants grow, their development is often limited by either too little or too much water. Drought limits growth more than flooding. About 40% of insurance indemnities for crop losses in the United States are for drought and about 20% are for excess water and flooding. In contrast, insurance indemnities for insect and diseases combined are only about 4%.

Since ancient times, man has been confronted with trying to make dry land productive, as documented by Samuel Noah Kramer of the University of Pennsylvania in Philadelphia, who translated the tablets of the Sumerians, as they were called by the third millennium B.C. The climate of their country, Sumer, is extremely hot and dry, and its soil, left to itself, is arid, wind-swept, and unproductive. The creative and resolute Sumerians turned Sumer into a Garden of Eden through use of irrigation water from the Tigris and Euphrates rivers, and their tablets tell us how they achieved this. [*See* IRRIGATION ENGINEERING: FARM PRACTICES, METHODS, AND SYSTEMS; WATER: CONTROL AND USE.]

Modern dryland research follows upon the basic principles of dryland farming, published in 1911 by John A. Widtsoe of the University of Utah. Widtsoe defined dryland farming as "the profitable production of useful crops, without irrigation, on lands that receive annually a rainfall of 20 inches [51 cm] or less." The methods of soil tillage of Jethro Tull (1674–1741) were at the foundation of Widtsoe's dry farming practices. The basis of the system is to store water in the soil by manipulating either the crops or the soil. Drought-resistant crops, proper tillage (disking, plowing, packing, harrowing), mulching to prevent evaporation, elimination of weeds, and fallowing are all important in dry farming. Several large international research centers focus their research on improving yields under dryland (nonirrigated) conditions. These centers include the International Maize and Wheat Improvement Center (CIMMYT) in Mexico; the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in India; and the International Center for Agricultural Research in the Dry Areas (ICARDA) in Syria. [*See* DRYLAND FARMING.]

If the soil is wetter than field capacity, plants may still take up water. But roots need at least 10% by volume air space in the soil to survive, because they obtain oxygen by diffusion from the air. If less than 10% of the soil bulk volume is open to air, then the air-filled pores will not be connected together in a continuous open path to the soil surface and needed oxygen cannot reach the roots to enable them to take up water and minerals. Also, carbon dioxide, evolved from the roots when they take in oxygen, cannot be

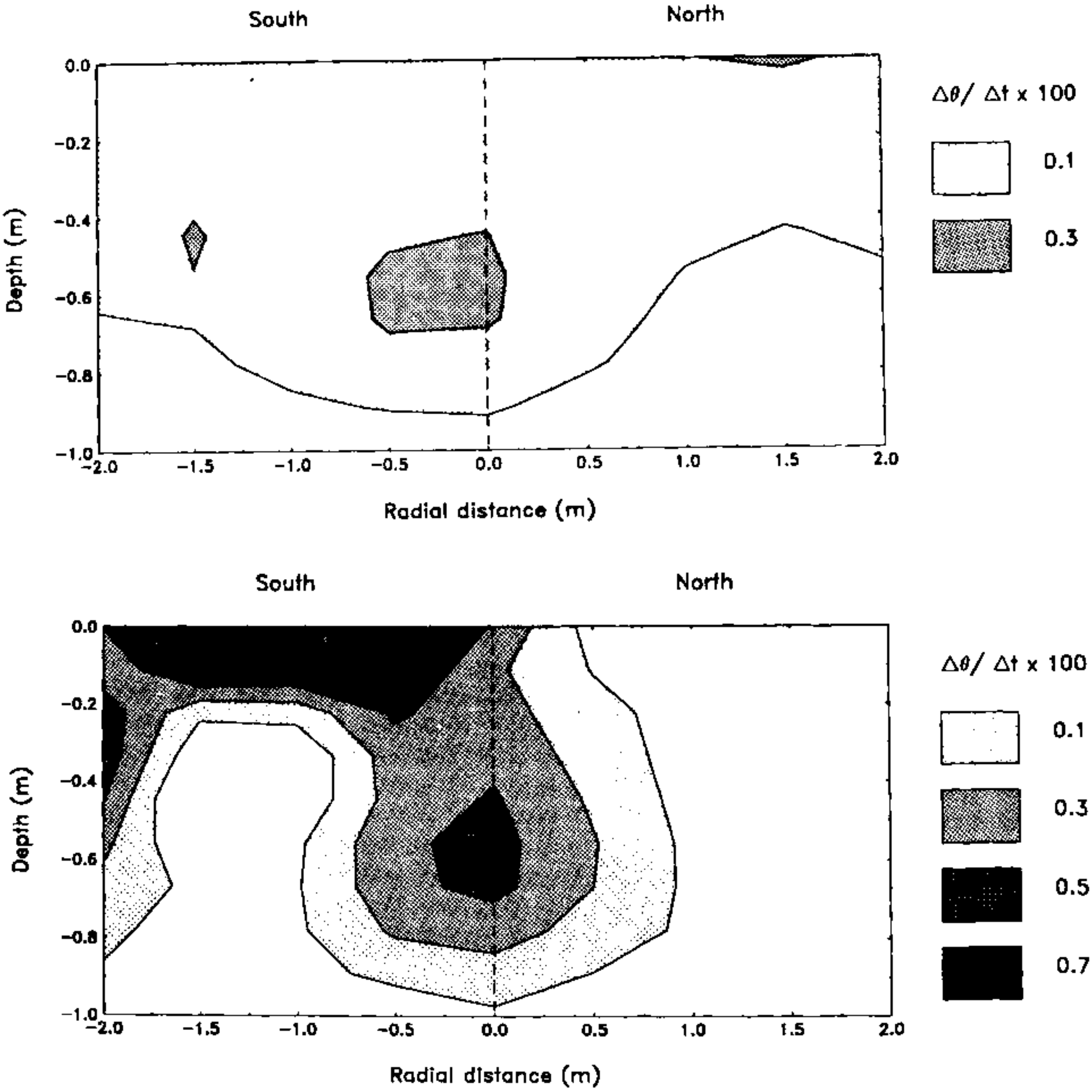

FIGURE 10 Measurement by time domain reflectometry of the changing spatial pattern of soil water content in the rootzone of a kiwifruit vine growing near Palmerston North, New Zealand. The upper figure depicts the average rate of water content change over the 4-week period 11 February–9 March 1992. The lower figure shows that change which occurred over the 2 weeks following irrigation of just the south side on 10 March. Rate of water extraction $\Delta\Theta/\Delta t$ is given in units of $m^3\ m^{-3}\ sec^{-1}$. The vine is located at the center. (From Clothier, B. E., and Green, S. R. (1994). Rootzone processes and the efficient use of irrigation water. *Agricultural Water Management* **25**, 1–12.)

removed from the soil when it is too wet. When a soil is flooded, gas exchange between the soil and air is drastically reduced, because gases diffuse much more slowly through water than through air.

C. Root Distribution in Relation to Soil Water

We will consider two examples from recent studies, one done under irrigated conditions and one done under dryland conditions. The two studies show the important relationship between root distribution and soil water.

Greater efficiency in the use of irrigation water will come through a better understanding of the distribution of root systems and the functioning of roots. A recent study done in New Zealand by Brent E. Clothier and Steven R. Green with roots of a kiwifruit vine documents the dominant role of surface roots

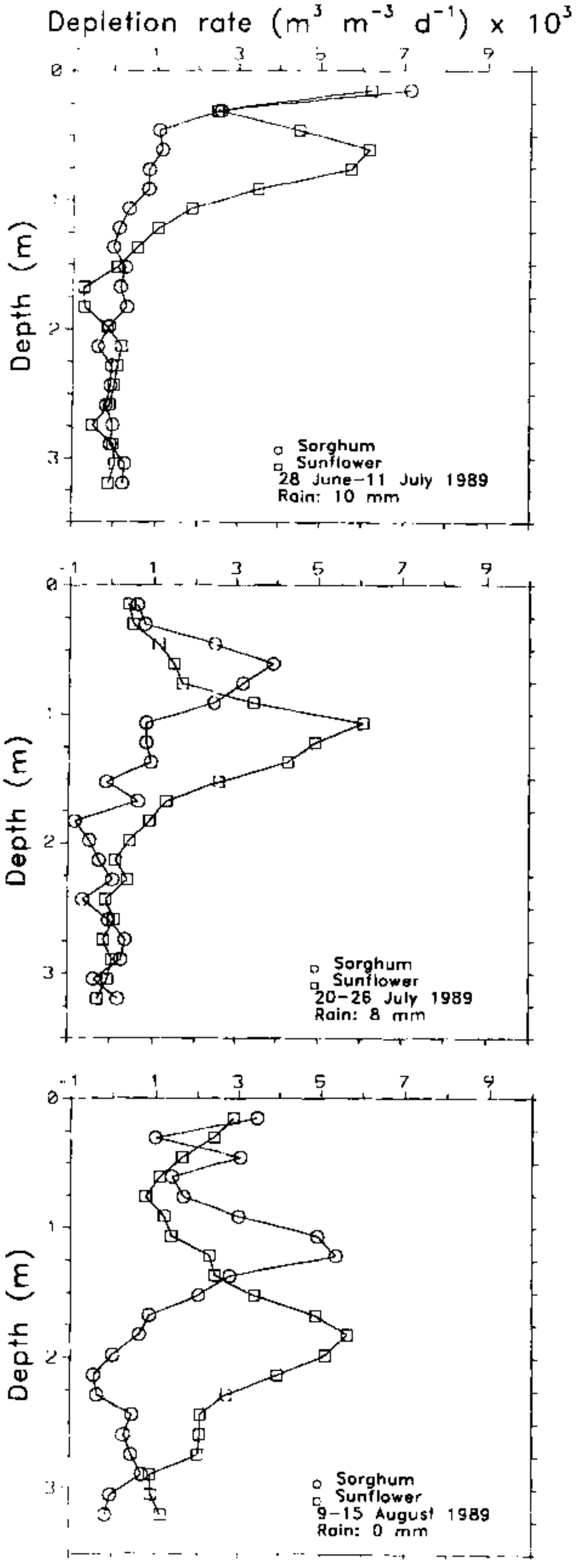

FIGURE 11 Soil water depletion rates of sorghum and sunflower during three periods in 1989: (a) 28 June to 11 July, (b) 20 to 26 July, and (c) 9 to 15 August. The depletion rates reported are multiplied by a factor of 10^3; therefore, 1 m^3 m^{-3} d^{-1} × 10^3 = 0.001 m^3 m^{-3} d^{-1}. (From Rachidi, F., Kirkham, M. B., Stone, L. R., and Kanemasu, E. T. (1993). Soil water depletion by sunflower and sorghum under rainfed conditions. *Agricultural Water Management* **24**, 49–62.)

in extracting water under irrigated conditions and demonstrates how irrigation can influence the spatial pattern of root water uptake. In this study, water content was measured by using time domain reflectometry (TDR), which permitted observations of the changing pattern of water content in the soil that occurs as a result of root water uptake (Fig. 10). This new technique for measuring soil water content was developed by G. Clarke Topp and colleagues in Canada in the 1980s and has improved our ability to determine water extraction patterns by roots. In the kiwifruit study, after an initial irrigation, the soil water content was uniform across the rootzone; also, the water uptake rate was quite uniform (Fig. 10, top). Beginning in the 10th week of 1992, just one half of the vine's root zone, the southern half, was wetted by a sprinkler irrigation. Following this differential irrigation of the rootzone, the flow of water in the "wet" southern root increased, but the flux in the "dry" northern root was about halved. Thus, the vine quickly switched its pattern of uptake away from the drier parts of its root zone.

Of greater interest, however, was the depthwise pattern of root uptake observed on the wet side. The preference for near-surface water uptake can be seen (Fig. 10, bottom). The vine continued to extract water in the densely rooted region surrounding its base, but the shift in uptake to the surface roots on the wet southern side was remarkable.

The results show that greater efficiency in irrigation water might be obtained by applying small amounts of water, more frequently. A small amount of irrigation water would be rapidly used by active, near-surface roots. This would then eliminate drainage of irrigation water into the lower regions of the rootzone, where draining water passes by inactive roots and goes to greater depth. The importance of surface roots shows the need for small, high-frequency irrigations.

Under rainfed conditions in semi-arid regions, however, it is important to have crops that exploit water at all depths in the soil, not just the surface, to make maximum use of agricultural water. A crop that depletes water in the upper soil zone could be followed by a crop that depletes water lower in the soil zone. Thus, the water in the entire soil profile would be available for uptake by crops. Two drought-resistant row crops in semi-arid areas are grain sorghum and sunflower. A recent study done in Kansas showed that the two crops use water at different depths in the soil. Sunflower depleted water to a deeper depth, and had a higher rate of depletion at lower depths, than sorghum (Fig. 11). The results suggest that deep-rooted crops might be planted in rotations with shallow-rooted crops or after irrigated crops to take advantage of water at depth. In a soil with macropores, sunflowers might be grown, because their deep roots would take up water that bypasses the rootzone of shallow-rooted crops.

VII. Conclusion

All terrestrial life depends on soil and water. Civilizations have risen and fallen based on the use or abuse of these two prime resources. This article has tried to explain some of the basic concepts underlying soil–water relationships. A fundamental understanding of water in soil should permit agricultural practices that can be based on sound, scientific principles. With such knowledge, we should be able to sustain the thin layer of wetted soil on the earth's surface, upon which all life is dependent.

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Sorghum

LLOYD W. ROONEY, F. R. MILLER, *Texas A&M University*

Glossary

Bird resistant sorghum Sorghum that contains a pigmented testa with condensed tannins that cause the birds to prefer other food sources; birds eat the bird resistant sorghums when other food is unavailable

Brown sorghum Sorghums containing a pigmented testa and condensed tannins; kernels may appear brown or white because of other characteristics

Decortication Process of removing the pericarp and associated layers from a sorghum kernel by abrasive action; often called dehulling and is done by hand in a mortar and pestle in Africa; the decorticated grain is crushed and used as flour or meal in various products

Phenolics Compounds containing a phenol ring which includes tannins, flavanoids, phenolic acids, and others

Plant color Secondary color of the sorghum tissue (purple, red, and tan are the major colors)

Waxy sorghum Contains only amylopectin in the starch granules; surface of the cut kernel has a wax like appearance

Weathering The deterioration of sorghum in the field by molds, sprouting, and other factors

Sorghum (*Sorghum bicolor*) is a major cereal crop grown in hot, semiarid tropical and dry temperate areas of the world. It is a coarse grass that is heat and drought tolerant. It is the major staple produced in areas of Africa and India, where it is processed into many different traditional foods. Sorghum varies in height and maturity. Hybrid (F_1) sorghums are grown in developed countries and varieties are used in other areas. Sorghum provides large quantities of forage and stover for livestock and building materials and fuel. Sorghum grain is similar to maize in composition and processing properties. It is high in starch and protein content, and its nutritional value is similar to that of maize when it is properly processed. Sorghum is used mostly for livestock feeds in the Western Hemisphere, where it is processed prior to formulating into rations. Sorghum is dry milled into grits, meal, and flour. It is used as an adjunct in brewing lager beer and for malt to produce opaque beer in Africa. Sweet sorghums are used to produce sorghum syrups and molasses. Sorghum hybrids have been improved for yield, disease and insect resistance, and quality by use of germ plasm from the world collection.

I. Introduction

In terms of total world crop production, sorghum [*Sorghum bicolor* (L.) Moench] ranks fifth, with 59 million metric tonnes of total production in 1988. Seventy-eight percent of the sorghum is planted in developing nations. The production of sorghum is concentrated in the United States, Mexico, Nigeria, Sudan, Ethiopia, India, and China. Most African and Asian countries use tall sorghums for food, feed, forage, fuel, and building material. In the Western Hemisphere, sorghum is mainly used for feed and forage. Specialty types are used for syrup, sugar, and alcohol on a limited basis.

The sorghum plant originated in the northeast quadrant of Africa. It belongs to the Graminae family, Panicoidea subfamily, and Andropogeneae tribe. Many different taxonomic forms and varieties exist within the species. The commonly used grain types have a large erect stem terminating in a semicompact to compact panicle, whereas the grassy types have smaller stems and narrower leaves, tiller profusely, and have long, lax panicles. The crop is generally handled as an annual, but under some conditions, ratoon cropping of old stubble is a general practice. It is a warm-season, annual crop favored by high day and night temperatures and intolerant of low temperatures. In temperate environments, time from sowing to maturity averages 110 to 140 days. Sorghum plants range in height from 0.6 to 6 m and possess a monoic-hermaphrodite flower that generally self-pollinates. The grain develops on a branched terminal panicle that can be compact or very open. Flowering proceeds from the top of the panicle downward, with each panicle containing from 800 to 3000 kernels.

There is an enormous range of diversity in the sorghum species. The World Sorghum Collection maintained in India has more than 30,000 entries. Sorghum is classed as grain sorghum, forage sorghum, grassy or Sudan-type sorghums, and broomcorn. The latter is grown for its long, fibrous panicle branches that are used to manufacture brooms. The grain of sorghum is classed according to pericarp color (white, yellow, or red), presence or absence of a pigmented testa (with or without tannins), pericarp thickness (thin or thick), endosperm color (white, heteroyellow, or yellow), and endosperm type (normal, heterowaxy, or waxy). These kernel characteristics are genetically controlled. Plant color of sorghum is tan, purple, or red. The tan plant sorghums with a white pericarp are considered to have excellent quality for food processing. A great deal of variation exists in sorghum attributes. For example, a black sorghum found in the western Sudan has very high levels of anthocyanins and condensed tannins.

II. Plant Characteristics

A. Growth and Development

The growth and development of a sorghum plant is similar to that of other cereals. Seed sizes range from approximately 5 to over 80 g per 1000 mature seeds. There is very little association of plant size to seed size. Different types of endosperm affect seedling emergence and vigor, that is, waxy, sugary, floury, and gradations of softer textures. High-quality seed of normal texture germinate rapidly in the soil at temperatures above 16°C. Minimum temperature for germination of sorghum seed is 7 to 10°C, depending on cultivar. Newly emerged seedlings can withstand freezing temperatures (−2 to −3°C) for a short period of time, but more mature plants are killed by freezing temperatures. Optimum temperature for growth appears to be approximately 27 to 30°C, but is modified by drought, wind, and relative humidity. Sorghum is a short-day plant because floral initiation is hastened by short days (less than 12 hr) and delayed by longer days. F. R. Miller and colleagues demonstrated that varieties have different photoperiod requirements and some varieties respond to differences in day length of as little as several minutes.

B. Maturity and Height

Generally, temperate grain sorghum hybrids require 100 to 140 days from planting to maturity. In tropical areas, the crop is usually planted prior to the onset of rains, and harvest is completed after the rains have subsided. Yield and maturity are related phenomena. Yields generally increase as time to maturity increases, up to a point where the requirements for growth become limiting, then yield decreases. Sorghum varieties and hybrids differ in their ability to tolerate different plant populations, fertility, and irrigation levels. Some hybrids respond differently to insecticides and weed control chemicals. They also respond differently to stresses and production technologies. The yield is variable, and the best cultural practices should be applied to obtain the full potential of each hybrid.

Sorghum height is a variable trait that is under simple genetic control. In most areas of the world, taller plants are preferred, but in those areas where mechanical harvesting is practiced, shorter stature is required. Among presently grown materials, there is a positive correlation between height and yield. As height is increased above 1.5 m, problems of lodging also become important. Height is controlled by four recessive, nonlinked, brachytic dwarfing genes. A single recessive gene may reduce height by 50 cm or more. Most grain sorghum hybrids developed in the United States are recessive at three height loci (three dwarfs), generally dw_1, Dw_2, dw_3 and dw_4. The dw_3 gene is unstable, and mutations to dominance result in a higher than normal frequency of tall plants in otherwise short hybrids.

Maturity in sorghum has been used to regulate the time of harvest to escape grain deterioration, seed molds, and insect damage and to maximize yield. There is a wide array of maturity differences from 60 to 300+ days to maturation. When sorghum varieties differ in maturity, it is the result of a response to temperature and photoperiod. Research has demonstrated that maturity differences in most sorghum cultivars are controlled by four genes (Ma_1, Ma_2, Ma_3, and Ma_4) and an allelic series at each locus. Rate of growth is reflected through maturity differences and total leaf production is correlated to maturity. Rate of leaf production varies only between 2.8 and 3.5 days per leaf, furthermore, both height and rate of growth are limited under stress conditions.

The genetics of height and maturity of sorghums grown primarily in the Americas are understood sufficiently to permit easy manipulations of that germ plasm. However, the American material represents a rather limited genetic base from which single-gene mutations have been selected. It is unreasonable to believe that all the variation in height and maturity among diverse sorghums can be explained by these genes. However, height does appear to be more simply controlled than does maturity, at the World Collection level.

C. Morphology

Grain color varies from white translucent to a very deep reddish-brown with gradations of pink, red, yellow, brown, and intermediates. Grain color is determined by pigmentation in the pericarp, testa, and endosperm. Specific genes determine the color of each of these parts. Pericarp color is controlled by R-Y-genes. A red pericarp contains R-Y- genes, white pericarp contains rryy or R-yy genes, and lemon yellow pericarps are rrY-. A pigmented testa occurs when B_1-B_2-ss and B_1-B_2-S- are present. These genotypes (B_1-B_2) contain condensed tannins and are referred to as brown sorghums. The pericarp color of a sorghum with B_1-B_2-S- genes is brown regardless of the pericarp genetics. White grain is preferred for human food and milling; brown has been generally found undesirable because of its bitter taste, intense color, and seed dormancy. However, brown sorghums are grown in certain areas of the world because they are more resistant to molds, weathering, and bird attack. In some areas brown sorghum is grown because other sorghums are destroyed. Argentina grows a high proportion of brown, bird-resistant, high-tannin sorghum.

Red grain is most frequently grown in the United States, where it is used primarily for livestock and poultry feed. However, larger quantities of white sorghums are grown in some areas because of good yields and improved quality of the white and yellow grains for processing. Most U.S. hybrids contain yellow endosperm genes that give the endosperm a pale yellow appearance. There is a strong movement toward production of tan plant hybrids. Disease or insect damage to the grain often causes colored spots in the pericarp and endosperm of sorghums with red and purple plant color. These stains affect grain appearance and processing properties.

The stem and leaf midrib are either sweet or non-sweet and dry or juicy, with gradations of both of these characteristics. Sweet stem is genetically recessive to non-sweet. These traits are important in forage sorghum quality and disease and drought resistance. Leaves of the sorghum plant appear alternately on the stem. In dwarf varieties, leaf sheaths overlap, but generally on taller types, portions of the internodes are exposed. Leaf size is a function of stem size and maturity. A cutinized layer covers the leaf and retards desiccation; during periods of drought, sorghum leaves infold or roll to reduce water loss.

The sorghum infloresence is a panicle, which varies in shape from compact to very open and lax and in size from 10 to 50 cm or more in overall length. Length and width of the panicle are inversely related. The panicle is a continuation of the vegetative axis. Primary branches appear at nodes within the panicle, and these branches are arranged in whorls, one above the other. The final branches bear one or several spikelets in which seeds are borne. Spikelets appear in pairs—the sessile one is fertile and the pedicellate one is staminate or neuter. Each sessile spikelet contains a primary and secondary floret. The ovary in the primary floret develops into the seed following fertilization. Some varieties that allow the development of both florets within the spikelet produce twin-seed. The seed are contained within the glumes and are covered by the glumes to varying degrees (25–100%).

D. Flowering

Anthesis occurs during the night or early morning hours, but is affected by climatic conditions. Flowering begins on the uppermost panicle branch and follows a regular downward progression and a horizontal plane around the panicle. If the pedicellate spikelets are staminate, a second wave of flowering begins at the tip moving downward after the primary wave has moved into the lower half of the panicle. The flowering process of one spikelet may be completed in 20 to 30 min, but the spikelet may remain open 2 or 3 hr. Flowering may span 6 to 15 days, depending on panicle size, temperature, and variety. A time span of 6 to 9 days (average 7 days) is usual; most of the spikelets on a panicle flower between Days 3 and 6. An adapted hybrid planted on uniform land generally completes anthesis in 10 to 15 days, but many stress factors cause nonuniformity. Anthers dehisce as they are exserted from the spikelet, or soon thereafter, and release pollen. A single panicle may produce from 20 to 100 million pollen grains. Stigmas are receptive for 1 to 2 days before anthesis and remain receptive for 8 to 16 days. Although sorghum is a self-pollinated species, natural outcrossing occurs and may range from 0 to 30+%, but averages less than 2%.

III. Sorghum Conversion Program

The cornerstone to sorghum improvement has been the tropical conversion program, a cooperative TAES–USDA project initiated in 1963, which changes tall, late-maturing tropical sorghum cultivars into short, early-maturing, nonphotosensitive types while retaining nearly 98% of the original genetic diversity. Tropical sorghums normally do not produce seed in temperate areas, thus the converted lines are extremely useful to sorghum breeders in temperate areas. Partially converted lines have been returned to Africa and have made significant improvements in sorghums in the tropics. Materials from the conversion program have dramatically changed the U.S. sorghum industry. Important economic traits obtained are disease and insect resistance; the stay-green trait, which improves drought tolerance; white grains on tan-colored plants, which produces improved quality; and many other properties. This long-term program continues to provide elite genes for sorghum improvement around the world. The benefits have been shared by sorghum programs through free exchange of elite germ plasm. Most new cultivars or hybrids released from sorghum programs have material from the conversion program in their pedigrees.

IV. Physiology

Sorghum has a lower osmotic concentration of the leaf juices than does maize, but that of the stem, crown, and root juices is higher in sorghum. Sorghum stems have a low moisture content and low transpiration ratio. Most data suggest that sorghum requires from 255 to 294 kg of water per kilogram of dry matter produced. Sorghum is slow to wilt and recovers well after rain or irrigation, making it more drought resistant than maize. Following drought induced wilting, sorghum leaves will recover within 5 days after watering. Whereas, maize was irreparably damaged.

Sorghum is not immune to drought however, high temperatures and moisture stress can affect growth, cause sterility problems, and substantially reduce yield. High temperatures between germination and floret initiation can result in lower grain yield. Plants exposed to high temperatures before floral initiation and at the late panicle development stage often have floret abortion.

Even though sorghum is drought tolerant, it responds well to supplemental irrigation. The amount of water required to produce maximum yields of sorghum is not a fixed value because temperature, relative humidity, wind, and soil moisture interact to determine the rate of both evaporation and transpiration. In some years the water requirement may drop to 41 to 46 cm and in a hot, dry year may go to 61 to 66 cm to produce maximum yields.

When sorghum plants begin to use water for germination, the rate for the first 2 or 3 weeks of development is slow (0.13–0.25 cm per day). A peak use of up to 0.84 cm per day may occur during the late boot and early heading stage, then water use rate averages about 0.64 cm per day from boot through the dough stage, which is a critical period. At this time sorghum will use about 7.6 cm of water in a 12-day period. Irrigation or water management is essential to maximize crop yields and includes land preparation methods and timing of irrigations, selection of planting seed, seeding rates, and amounts of fertilizer, herbicides, and insecticides.

Natural soil fertility is not generally sufficient to maintain a crop for maximum production. Sorghum requires relatively large amounts of nitrogen, phosphorous, and potassium; lesser amounts of calcium, magnesium, and sulfur; and small amounts of seven trace elements for proper plant growth. The most effective method to determine fertilizer needs is a soil test. The rule of thumb to follow in nutrient requirements for sorghum is that each 1000 kg of grain yield removes 13.6 kg of N, 4.5 kg of P_2O_5, and 13.5 kg of K_2O. Sorghum grows best when soil pH is between

6 and 7.5. If pH should drop below 6, lime can be added to bring it back into the optimum range.

At anthesis or approximately 60 to 70 days past emergence, about one-half of the total plant weight has been produced, and nearly 70% of the nitrogen, 60% of P_2O_5, and 80% of the K_2O have already been taken up. These values indicate the importance of nutrition during the early growth of the sorghum plant.

Within the first 30 to 35 days after plant emergence, nearly all growth is in the leaves. Floral differentiation occurs in photoperiod-insensitive material at approximately this time. Then the culm or stem begins rapid growth and continues until maximum leaf weight is reached (approximately 60 days) and maximum stem weight is obtained at 65 days past planting. The panicle size remains small and increases slowly in weight until about 18 days past differentiation, after which it increases rapidly in weight. Following pollination, the grain dramatically increases in weight, sometimes faster than the rate at which total dry matter accumulates in the plant. This lowers the stem weight because stored materials are moved from the stem to the developing seed. Most sorghums increase in dry weight until 30 to 38 days past anthesis, at which time maximum dry weight is attained. Maximum rates of dry matter accumulation occur 8 to 14 days past anthesis. More vitreous kernels reach harvestable moisture (12–15%) 45 to 60 days after anthesis. Softer kernels lose moisture at a slower rate.

V. Hybrids

In the more developed countries, sorghum is produced using F_1 hybrids provided by a sophisticated seed industry. Sorghum hybrids yield 20 to 50% more grain than varieties. They are more tolerant of drought and other adverse growing conditions. The yield increase comes from more grain per plant. Seed size is not significantly different between parents and the hybrid, although the hybrid has more leaf area and thus has a greater photosynthetic area. It has been suggested that the greater yield may be attributed to a more rapid cell division of the apical meristem.

Fertile sorghum hybrids are produced by growing specific parents (inbred lines) together in seed grower crossing fields (Fig. 1). Cytoplasmic male sterility is the key to hybridization in sorghum. Because the male-sterile plants do not disseminate viable pollen, these plants can be fertilized by pollen from the otherwise normal pollen-producing plants. Cytoplasmic–genetic male sterility is inherited maternally. This form of male sterility results from incompatibility between the cytoplasm of the female and nuclear factors contributed by the male parent. Cytoplasmic male sterility was found when cytoplasm from a milo sorghum was used with nuclear factors from kafir.

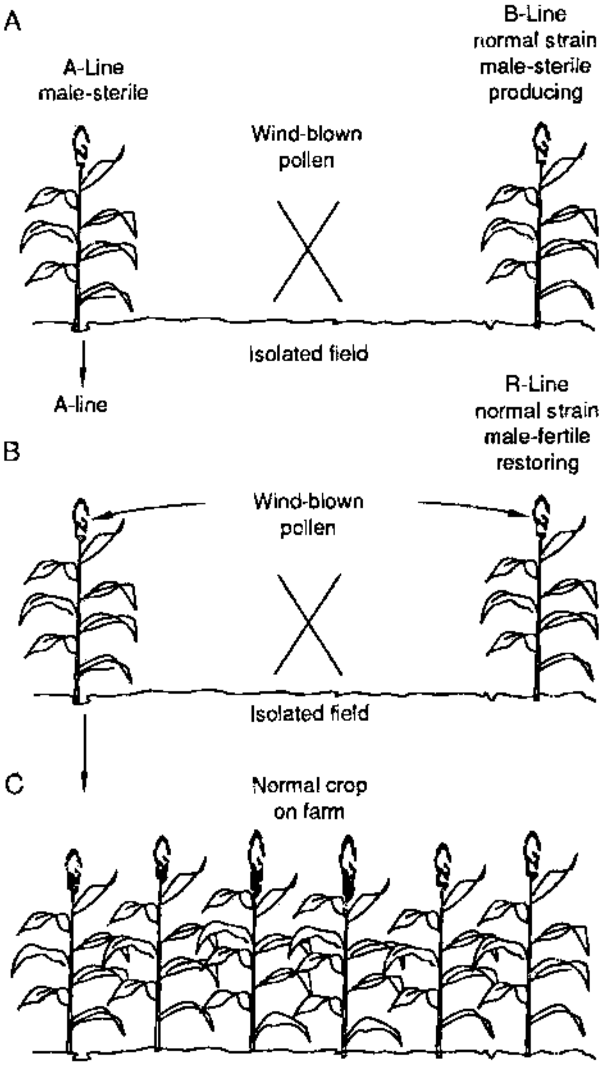

FIGURE 1 Methods for producing parental and hybrid seed of sorghum. (A) Parental crossing field; (B) Seed grower crossing field; (C) Single cross (A × R) sorghum hybrid.

Sorghum hybrids originated in Texas, thus male and female parents were derived from germ plasm selected in a temperate-zone climate. As a result of this, the first hybrids developed in Texas were not suited to tropical areas, where floral differentiation occurs in short days and grain fill is accomplished under increasingly hot nights, which causes reduction in harvestable yield. Tropically adapted temperate-zone sorghums have been developed that have increased grain yields in the tropics.

Yield of grain under dryland cultivation averages 1800 to 4000 lb per acre. Under irrigation, yields of sorghum grain range from 6000 to 12,000 lb per acre. Yield is dependent on specific hybrid potential, fertility, availability of water, cultural management, and related biotic and abiotic stresses. In many important sorghum producing areas, cultivars are grown because a seed industry does not exist to supply hybrids. This limits the productivity of sorghum.

VI. Grain Structure and Physical Properties

The sorghum kernel is considered a naked caryopsis, although some African types retain their glumes after threshing. The kernel weight varies from 3 to 80 mg. The size and shape of the grain vary widely among sorghum races. Commercial sorghum grain has a flattened-spherical shape 4 mm long, 2 mm wide, and 2.5 mm thick with a kernel weight of 25 to 35 mg. Bulk density or test weight and grain density range from 708 to 60 kg/m^3 and 1.26 to 1.38 g/cm^3, respectively.

The sorghum caryopsis is composed of three anatomical parts: pericarp, endosperm, and germ. The relative proportion of these structures varies but in most cases is 6, 84, and 10%, respectively. The pericarp is the fruit coat and is fused to the sorghum seed. It originates from the ovary wall and is subdivided into three distinctive parts: epicarp, mesocarp, and endocarp. The epicarp is the outermost layer and is generally covered with a waxy film impermeable to water. The mesocarp varies in thickness and contains starch granules. The dominant gene Z affects thickness of the mesocarp; homozygous recessive ZZ produces a thick, starchy mesocarp. The endocarp plays a major role during water uptake and germination.

The seed is composed of the seed coat (or testa), endosperm, and germ. The endosperm tissue is triploid, resulting from the fusion of a male gamete with two female polar cells, a double fertilization. The testa is derived from the ovule integuments; in brown sorghums, it is thick and contains condensed tannins. It is sometimes referred to as a subcoat or undercoat and can be purple or brown in color. In nonbrown sorghums the testa is difficult to find without high-magnification microscopy.

The endosperm is composed of the aleurone layer and peripheral, corneous, and floury areas. The aleurone consists of a single layer of rectangular cells adjacent to the tube cells or testa. Aleurone cells contain a thick cell wall, large amounts of proteins (protein bodies) and enzymes, ash (phytic acid bodies), and oil bodies (spherosomes). The peripheral endosperm adjacent to the aleurone layer is composed of dense cells containing large quantities of protein and small starch granules. These layers affect processing and nutrient digestibilities of sorghum. Processing by steam flaking, micronizing, popping, and reconstitution is designed to disrupt endosperm structure to improve digestibility.

The corneous and floury endosperm cells are composed of starch granules, protein matrix, protein bodies, and a thin cell wall rich in β-glucans and hemicellulose. In the corneous endosperm, the protein matrix has a continuous interphase with the starch granules with protein bodies embedded in the matrix. The starch granules are polygonally shaped and often contain dents from protein bodies. The appearance is translucent or vitreous. The opaque-floury endosperm is located around the geometric center of the kernel. It has a discontinuous protein phase, air voids, and loosely packaged round-lenticular starch granules and is opaque to transmitted light. Genetics and environment affect the proportions of floury to corneous endosperm (kernel texture) in sorghum kernels. Texture is related to grain hardness but is not the same.

The germ is diploid owing to the sexual union of one male and one female gamete. It is divided into two major parts: the embryonic axis and scutellum. The embryonic axis develops into the new plant; it is subdivided into a radicle and plumule. The radicle forms primary roots, whereas the plumule forms leaves and stems. The scutellum is the single cotyledon of the sorghum seed. It contains large amounts of oil (spherosomes), protein, enzymes, and minerals and serves as the connection between the endosperm and embryonic axis.

VII. Composition

Sorghum composition (Table I) varies significantly owing to genetics and environment. Starch (75–79%) is the major component, followed by protein (6.0–16.1%) and oil (2.1–5.0%). Protein content (N × 6.25) of sorghum is more variable and usually 1 to 2% higher than in maize. Approximately 80, 16, and 3% of the protein is in the endosperm, germ, and pericarp, respectively. Generally, sorghum contains 1% less oil and significantly more waxes than

TABLE I
Compostion of Sorghum Grain[a]

Component	Mean	Range
Protein N × 6.25) (%)	10.6	5.5–17.0
Ether extract (%)	3.4	2.2–4.0
Crude fiber (%)	2.5	2.0–3.0
Ash (%	2.0	1.8–2.2
Nitrogen-free extract[b] (%)	80.0	75–86
Starch (%)	74.1	68–78
Soluble sugars (%)	2.1	1.8–2.2
Essential amino acids[c] (g AA/100 g protein)		
Lysine	2.1	1.6–2.4
Leucine	14.2	12.0–16.3
Phenylalanine[d]	5.1	4.0–5.5
Valine	5.4	4.5–6.2
Tryptophan	1.0	0.7–1.2
Methionine[e]	1.2	1.0–1.6
Threonine	3.3	2.8–3.5
Histidine[f]	2.1	1.8–2.3
Isoleucine	4.1	3.7–4.7

[a] All values are expressed on a dry matter basis for sorghum samples analyzed in the past 27 years, excluding endosperm mutants.
[b] Calculated by difference.
[c] FAO/WHO suggested pattern (g AA/100 g protein): lysine, 5.44; leucine, 7.04; phenylalanine + tyrosine, 6.08; valine, 4.96; tryptophan, 0.96; methinine + cysteine, 3.52; threonine, 4.0; isoleucine, 4.0.
[d] Phenylalanine can be partially spared by tyrosine.
[e] Methionine can be partially spared by cysteine.
[f] Histidine is considered an essential amino acid only for children.

does maize. Sorghum starch is composed of 70 to 80% amylopectin and 20 to 30% amylose. Waxy sorghums contain starch with 100% amylopectin and have properties and uses similar to those in waxy maize. Amylopectin and amylose have an average molecular weight of $8–10 \times 10^6$ and $1–3 \times 10^5$, respectively.

The main protein fraction in the kernel is the prolamines (kafrins) followed by glutelins. The alcohol-soluble prolamine fraction comprises 50% of the protein. These proteins are hydrophobic, rich in proline, aspartic, and glutamic acids, and contain little lysine. They are mainly found in protein bodies and are affected by nitrogen fertilization. Glutelins are high-molecular-weight proteins mainly located in the protein matrix. The lysine-rich protein fractions, albumins and globulins, predominate in the germ. High-lysine sorghums such as "P-721" and some Ethiopian types contain lower and higher levels of kafrins and albumins/globulins, respectively. The higher-lysine sorghum cultivars are soft or dented and are not produced commercially.

Most of the fiber is present in the pericarp and cell walls. Aleurone and endosperm cell walls are associated with ferulic and caffeic acid. Around 85% of the dietary fiber is insoluble; it is mainly composed of hemicellulose and cellulose. The soluble fraction is rich in pentosans and β-glucans. Approximately 70 and 30% of the pentosan are alkali and water soluble, respectively.

The germ and aleurone layer are the main contributors to the lipid fraction. The germ provides about 80% of the oil. The fatty acid composition consists mainly of linoleic (49%), oleic (31%), and palmitic (14.3%) acids. Sorghum contains 0.1 to 0.3% of an indigestible carnaubalike wax that is located on the epicarp, and also on the leaves and sheaths. Refined sorghum oil is very similar to maize oil in quality.

Most of the minerals are concentrated in the pericarp, aleurone, and germ. The ash fraction is rich in phosphorus and potassium and low in calcium and sodium. Most of the phosphorus is bound to phytic acid. The germ and aleurone are rich in fat-soluble and B vitamins. Carotenes are found only in yellow and heteroyellow endosperm cultivars. The carotenes are bleached by the sun; levels in mature grain are significantly lower than those of yellow maize.

All sorghums contain phenolic acids and most contain flavonoids, but only brown sorghums contain condensed tannins, which protect the kernel against preharvest germination and attack by insects, birds, and molds (fungi). Brown sorghum always have a pigmented testa (B_1-B_2-ss) and some have tannins in the pericarp (B_1-B_2-S-). Sorghums without a pigmented testa do not contain any condensed tannins. Birds can and do consume brown sorghums when other food is unavailable; in fact, animals consume greater amounts of bird-resistant sorghums (brown) than nonbird-resistant (nonbrown) sorghum in rations. The amount of weight gain is similar, but the feed efficiency is lower with brown sorghum. Sorghum does not contain any tannic acid, although some articles erroneously report condensed tannins as tannic acid. Assays for tannins based on colorimetric procedures for phenols give unreliable data for sorghum.

VIII. Market Classes

The Federal Grain Inspection Service (FGIS) recognizes four classes of sorghum: sorghum, white sorghum, tannin sorghum, and mixed sorghums. The class sorghum contains sorghum kernels with any color pericarp and endosperm as long as they do not contain a pigmented testa. The white sorghum class consists of kernels with white or colorless pericarp without a pigmented testa. The tannin sorghum class has kernels that contain pigmented testa and condensed tannins. Mixed class sorghum has more than 3% of tannin sorghum in other sorghum grains. The tolerance levels for foreign material were reduced in 1992.

In South Africa, sorghum standards have been established for malting and feed sorghums. The brown or tannin sorghums are not desired for malting by commercial maltsters. Brown sorghums can be malted by using special procedures to inactivate the tannins. For traditional malting by local artisans, the brown sorghums are malted because the white sorghums are preferred for food.

It is difficult to distinguish brown or tannin sorghums from red or even white sorghums in market channels. The FGIS uses a chlorox bleach test to determine sorghum kernels with a pigmented testa. The bleach/alkali removes the pericarp and the black or intense brown kernels with a pigmented testa can be easily identified when compared with standards. The percentage of brown kernels can be determined and is generally related to quantity of tannins. Argentina and a few other countries produce high-tannin sorghums for export, although the tannin content significantly reduces the value of sorghum.

IX. Traditional Uses of Grain

A. Milling

Thirty percent of world sorghum production is consumed directly by humans. For production of most traditional foods, sorghum is first dehulled with a wooden mortar and pestle. The grain is usually washed, placed in the mortar, and pounded vigorously with the pestle. The abrasive action frees the pericarp from the kernel above the aleurone layer on a nonbrown sorghum. Thick pericarp cultivars with hard endosperm and round kernels are preferred for dehulling or decortication. The bran or pericarp is separated from the grain by washing with water or by winnowing the sun-dried grain. Most sorghums are decorticated to remove 10 to 30% of the original grain weight depending on kernel hardness. It is impossible to dehull soft kernels because they disintegrate. Mechanical decortication with rice milling equipment or abrasive disks is becoming more popular in many countries, particularly in urban areas.

The decorticated kernels are reduced to flour by hand pounding in the mortar and pestle. However, in urban areas, the housewife takes the dehulled grain to a small mill, where it is milled into flour or meal. The mill usually uses attrition mills with stones or steel plates that produce a smooth-feeling flour. Flour is sieved to obtain fractions with acceptable particle size for specific products. Attrition milling gives better flours than hammermilling, which produces gritty flour that imparts harsh texture to sorghum products.

The milled products from sorghum have a short shelf life because they contain lipids, thus the women mill sorghum daily. The lack of shelf-stable sorghum products is a major disadvantage. Many consumers have switched from sorghum foods to other cereals that are convenient to prepare.

B. Traditional Food Uses

The major categories of traditional foods are fermented and unfermented flat breads, fermented and unfermented thin and thick porridges, steamed and boiled cooked products, snack foods, and alcoholic and nonalcoholic beverages. Worldwide, the most popular unfermented flat breads are roti in India and tortillas in Central America. For rotis, a portion of the flour is gelatinized, mixed with more flour and warm water, and kneaded into a dough. The dough is shaped or rolled into a circle that is baked on a hot griddle. For tortilla production, whole or decorticated sorghum is lime-cooked, steeped overnight, washed, stone ground into a masa, shaped into thin circles, and baked on a hot griddle. The disc puffs during baking. Fresh roti and tortillas have good flavor and texture but they stale rapidly.

The most popular fermented breads are injera, kisra, and dosai consumed in Ethiopia, Sudan, and India, respectively. About 80% of the Ethiopian sorghum is used for production of injera. To make injera, the sorghum flour is mixed with water and a starter from a previous batch of injera. Part of the fermented batter is cooked to gelatinize the starch, cooled, and added to the fermenting batter. Then after fermentation for 24 to 48 hr, the batter is poured onto a covered greased pan for baking. The fermentation is very active, so many small bubbles form on the surface of the bread. Baked injera is a large, thin, flexible bread with many uniformly distributed air bubbles (fish eyes) on the surface. Kisra is similar but is much thinner. Dosai is produced from a mixture of black gram, sorghum, and rice flour. These products are consumed with spicy fillings and have excellent taste.

Porridges are fermented or cooked with acid or alkali. Tô is an unfermented stiff porridge very popular in West Africa. Decorticated sorghum flour is cooked in plain water or water acidified with tamarind juice or made alkaline with the leachate of wood ashes (potash). Popular fermented porridges are ogi and nasha consumed in West and East Africa, respectively. For these, whole sorghum is soaked in water and allowed to ferment for 2 to 3 days. The wet grain is crushed in a slurry of water and sieved to remove the bran. The throughs are allowed to ferment longer. Excess water is decanted and the resulting slurry cooked in water or milk.

For couscous production, sorghum flour is kneaded with enough water to form agglomerates. The particles are forced to pass through a coarse screen and then steamed. Sometimes the cooked couscous product is sun-dried, screened to a given particle size, and used as a convenience food. It is rehydrated when required. Couscous is eaten with special sauces and is an excellent food, but tedious to prepare. Decorticated sorghums are often cooked like rice. Special types of small-seeded, very hard sorghums are used as a substitute for rice.

Opaque beer is a traditional alcoholic beverage produced from malted sorghum. The sorghum is soaked in water for 12 to 24 hr and allowed to germinate for several days until the sprouts reach a certain stage. The germinated sorghum (malt) is sun-dried, crushed, and mixed with water, which is heated and held long enough to allow the malt enzymes to convert the starch into sugars. Then it is filtered to remove some of the sprouts and pericarp pieces. The filterate is brought to boiling, cooled, and placed in a fermentation pot that contains yeast from a previous batch of beer. Fermentation occurs overnight or longer and the beer is drunk while actively fermenting. The beer has high solids content, a low pH, a sour flavor, and a pink or red color when produced from red or brown sorghums. There are many variations in the type of opaque beers, with some sweet, nonsour products that are very good tasting. The length of fermentation and the extent of souring are related. Most opaque beer is very sour.

X. Industrial Uses

A. Wet Milling

Industrial uses of sorghum are similar to those of maize. Sorghum is wet-milled to produce starch with properties and uses similar to those of maize starch. Sorghum is more difficult to wet-mill than maize, and sorghum by-products are less desirable. Sorghum is wet-milled in the Sudan and possibly in Nigeria, where the grain is significantly less expensive. Wet-milling of sorghum in the United States was discontinued in the 1970s for economic reasons.

B. Sweet Sorghum

Sweet sorghum biomass, the entire above ground portion, is used for ethanol production. Yields of alcohol (182 proof) per tonne of sorghum grain are comparable to those of maize (387 vs. 372 liters). The commercial technology required to ferment sweet sorghum biomass into alcohol has been highly developed in Brazil. One tonne of sweet sorghum biomass has the potential to yield 74 liters of 200 proof alcohol.

C. Sorghum Syrup and Molasses

Sweet sorghum types are available that have been used to produce syrup and molasses, and special varieties are grown. The plants are cut, stripped of leaves, and pressed to force sap from the stalks. The juice is evaporated to form a strong-tasting syrup that is referred to as sorghum molasses. This process is common in the southern United States. Alternatively the juice can be processed and used for sugar production. This procedure is well developed but is not used commercially. Sorghum molasses or syrup has a strong aroma and unique flavor.

D. Dry Milling

Sorghum has been dry-milled into a wide variety of products, including low-fat grits, flour, acid-modified flour, and other products. The sorghum is tempered, decorticated with abrasive mills, and degerminated by impaction. The germ is separated from the endosperm particles by gravity separation. Good yields of low-fat grits are possible, especially with the new white, harder endosperm sorghum grains. The grits are used as a brewing adjunct in production of lager beer depending on the relative price of competing adjuncts. The most desirable grit has light color, bland flavor, and low oil content. The grits have been fortified with soy grits and used in U.S. food aid shipments to Africa, where sorghum is preferred.

E. Malting

Sorghum malt is produced extensively in South Africa. Pneumatic malting and floor malting is used.

The malt is used for alcoholic beverages, weaning foods, and breakfast foods. Sour opaque beers are produced commercially in large factories. Sorghum malt is mixed with cooked maize grits and allowed to sour for several hours. Then the soured mixture is added to additional malt and cooked corn grits to saccharify the starch. Finally, the mixture is incubated with yeast and consumed as a sour, opaque, actively fermenting beer. Sorghum malt is preferred for color and flavor. A significant portion of the sorghum grown in southern Africa is used for industrial malting. Prepared malts and beer powders for home brewing are popular products in South Africa. [*See* BREWING TECHNOLOGY.]

In Nigeria, sorghum and maize are being used to produce lager beer without barley malt following the government ban on the importation of barley and barley malt. Therefore, Nigerian breweries are producing clear (lager) beer from a combination of malted sorghum, sorghum and/or maize grits, and commercial enzymes that convert the starch to fermentable sugars. Sorghum malt has low diastatic power so commercial enzymes are required. In many processes, sorghum malt is not used because malting causes considerable dry matter losses. Economically, the use of grits and commercial enzymes is practical. The clear beer is of good quality with slightly different taste and keeping properties compared to those of barley malt lager beer. Recently, the ban on barley has been lifted in Nigeria.

F. Baked Products

Sorghum grits, meal, and flour can be used to produce a wide array of baked goods when mixed with wheat flour. Sorghum does not contain gluten, thus the amount of sorghum flour in the blend depends on the quality of the wheat flour, the baking procedure, formulation, and quality of the baked products desired. It is possible to produce nonwheat sorghum–cassava starch breads by gelatinizing the cassava starch. Such breads have intermediate loaf volume and stale rapidly.

G. Snacks and Cereals

Sorghum can be puffed, popped, shredded, and flaked to produce ready-to-eat breakfast cereals. Extrusion of sorghum produces acceptable snacks, cereals, and precooked porridges. Waxy and heterowaxy sorghum hybrids produce tender extrudates with excellent mouth feel. Micronized waxy sorghum flakes give granolas excellent texture.

XI. Nutritional Value

Sorghum has proximate composition, amino acid contents, and nutritional value similar to those of maize. However, because of its lower fat content, sorghum usually has slightly lower gross, digestible, and metabolizable energy than does maize. The protein digestibility of sorghum is 5% lower than that of maize. However, fermentation, malting, and other processing methods significantly improve nutritional value. Brown sorghums have lower nutritional value than sorghums without tannins; tannins lower protein digestibility and feed efficiency. Malting significantly enhances the digestibility and biological value of sorghum. Malted brown sorghums have greatly improved nutritional value, and decortication improves their protein digestibility and reduces their tannins.

Lysine and threonine are the first and second limiting amino acids of sorghum. There are high-lysine cultivars that contain approximately 50% more lysine and promote better weight gains in weaning rats. However, they have soft, floury endosperms and produce low yields of grain. Research to develop sorghum hybrids with harder endosperm and higher lysine continues with slow progress. The high-lysine types found in Ethiopia continue to be grown on a limited basis because they have excellent taste.

XII. Animal Feeds

The feeding value of sorghum for livestock species is generally considered to be 95% or more of the feeding value of yellow, dent maize. Brown sorghums are considered to have 85% of the feeding value of maize. Sorghum must be properly processed to enhance its digestibility. Poultry and swine feeds use ground sorghum extensively depending on relative costs and feeding value. Because sorghum is low in yellow pigments, additional carotenoids are used in rations where yellow-pigmented broilers are desired. [*See* FEEDS AND FEEDING.]

Sorghum is used extensively for dairy and beef cattle rations. In feedlots in the Great Plains, sorghum comprises 60 to 80% of the diet. Sorghum in these feedlots (up to 200,000 head) is usually steam-flaked and mixed with roughage and supplements and fed to the cattle immediately. The grain is sieved to remove foreign material, conditioned to about 18% moisture, steamed for 15 to 30 min, allowed to equilibrate for 15 min at 100°C, and flaked by large rollers. For good feed efficiency, the flakes of sorghum must be very thin and resistant to breakage during handling. The addition of moisture to the grain is an advantage to the feedlot operator.

Popping, micronizing, exploding, and reconstitution have been used to process sorghum for feedlot cattle. These methods, if properly used, will yield the feeding efficiency of steam-flaked sorghum. They afford an advantage for smaller feedlots because a source of steam is not required. Reconstitution and early harvesting require less energy for processing, but grain storage is a costly problem.

XIII. Sorghum Improvement

In the United States, new sorghum inbreds with white kernels and tan plant color have been released by the Texas Agricultural Experiment Station. They produce new hybrids with significantly impoved food, feed, and processing properties combined with good agronomics and tolerance to production hazards. A number of seed companies are developing or have released white or yellow hybrids, some with tan plant color. The tan grains have reduced levels of anthocyanin pigments and produce processed feeds with a light color. These improvements make sorghum more attractive for use in feeds and foods. For example, the white sorghums produce lighter-color grits at significantly higher yields than do red sorghums. White, tan plant homozygous, and heterowaxy hybrids are available for use in specific applications. The waxy grain has interesting processing properties, including greater expansion during extrusion, tender flakes useful in granola, and significantly improved steam-flaking characteristics. Some data suggest that waxy grains are more efficiently utilized by ruminants and swine.

International sorghum improvement was begun fairly recently, yet significant improvement has been made in sorghum yields and grain quality in many areas. However, in West Africa the new improved sorghums were attacked by head bugs and molds that essentially destroyed the grain. Efforts to breed sorghums with resistance to molds and head bugs have been only partially successful. Only photosensitive varieties consistently escape the head bugs, so efforts to increase yields have been largely thwarted. Improved local photosensitive types with tan plant and good-quality grain for food processing are required. Sorghum is an important food and feed crop that will continue to be improved by commercial seed companies and government research activities.

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Soybean Genetics and Breeding

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Glossary

Cultivar Strain of plants, developed by breeding and selection, that is uniform in characteristics and grown under cultivation; soybean cultivars are inbred lines, phenotypically homogeneous, and genetically stable

F_1, F_2, F_3, etc. Designation used for successive generations of inbreeding or filial generation; F_1 is the immediate progeny of a cross, the F_2 the self-pollinated progeny of the F_1, the F_3 the self-pollinated progeny of F_2, etc.

Genotype Genetic make-up or identified genes of an individual; genes may be identified by observable traits of individuals or their progeny

Heritability Extent to which traits are controlled by the genotype of an individual or strain and are transmitted from parent to offspring; heritability is often expressed as the ratio of genotypic to phenotypic variability and may be expressed as a percentage

Inbred line In soybean breeding, a line developed by successive generations of selfing, following hybridization, in which individuals making up the inbred lines are phenotypically homogeneous and genotypically homozygous; inbred lines with superior attributes may be designated as cultivars

Linkage group Association of genes that tend to be inherited together because of their proximity on the same chromosome; genes in different linkage groups are inherited independently

Phenotype Observable traits of individuals that are due to the interaction of the genotypes, or genetic constitutions, of the individuals with the environment

Restriction fragment length polymorphism (RFLP) Fragment of DNA that has been cut by enzymes, and identified by electrophoretic techniques; these RFLPs are used as marker sites on chromosomes that make up the soybean genome

Transgenic plants Genetic modification of a plant's genome by inserting DNA from different genotypes, usually from different species; transgenes are the genes transferred from different donor genomes and expressed in the recipient genome

Soybean, one of the world's major oilseed crops, is grown commercially in nearly 50 countries. Soybean oil is the major edible vegetable oil produced in the world; the residual meal is an important high-protein supplement of livestock feeds. Soybean genetics deals with the inheritance of both simple and complex traits of the plant, many of which are important in the development of improved cultivars. Various breeding methods are used to develop cultivars with high seed yield, resistance to pathogens, and seed compositional traits important in the utilization of the crop.

I. Introduction

The soybean, *Glycine max* (L.) Merr., introduced from China in the late 1700s, was not grown commercially in the United States until the early 1900s. Initial production of soybean was primarily for hay or silage or the crop was plowed into the soil as a green manure. It was not until 1941 that the U. S. acreage of soybean harvested for seed exceeded the acreage harvested for forage and other purposes. Soybean, grown on about 24 million hectares, is now the major oilseed crop produced in the United States and the residual meal is the primary source of high-quality protein in livestock feed rations. [*See* Soybean Production.]

Soybean seed of commercially grown cultivars averages 41% protein and 21% oil, on a moisture-free seed basis. About 95% of the oil is used as an edible oil in salad or cooking oils, and in margarines and shortenings. Industrial uses of the oil include components of paints, varnishes, plastics, lubricants, and printing inks. Soy protein has an excellent balance of essential amino acids, with only the sulfur containing amino acids slightly lower than the requirements for an ideal feed. Soybean meal is a key ingredient in pet and livestock feeds and is the primary source of protein in poultry rations. Less than 5% of soy protein is used for edible purposes as soy flour, protein concentrates and isolates, textured proteins, and in specialty foods such as tofu.

Soybean breeding programs were initiated in the United States in the 1930s by scientists in the U. S. Department of Agriculture (USDA). Early released cultivars were direct selections from soybean germplasm introduced from China, Japan, and Korea. The first cultivar developed from hybridization was "Lincoln," released in 1944. Almost all cultivars released in the United States prior to 1970 were developed by USDA-Agricultural Research Service (ARS) and State Agricultural Experiment Station soybean breeders. These cultivars were grown on virtually all the U.S. acreage planted to soybean. The Plant Variety Protection Act, passed in 1970, provided protection to breeders of self-pollinated crops against unauthorized production of cultivars. This encouraged cultivar development by commercial interests and now most of the soybean acreage in the northern United States is planted to cultivars developed by private companies. In the southern United States a greater portion of the acreage is planted to cultivars developed by publicly funded breeding programs. [*See* Cultivar Development.]

The soybean is a self-pollinated plant and the small amount of outcrossing that occurs, less than 1% is due to pollen transmission by insects. Controlled pollinations between selected parents are tedious to make and result in one to three seeds per successful pollination. The mode of pollination and difficulty in making controlled crosses affect breeding methods used to improve the soybean. Released cultivars are genetically stable inbred lines, maintained by harvesting pure seed of each cultivar.

II. Qualitative Genetics

The soybean has a 2*n* chromosome number of 40 and is considered to be a functional diploid of polyploid origin. Genetic studies have identified over 200 loci, some with multiple alleles, that control reaction to pathogens and insects, plant growth and morphology, physiological and biochemical traits, and chemical composition of the seed. About 70 loci have been associated in 19 linkage groups, or segments of chromosomes.

Biochemical techniques have been used to identify small fragments of DNA electrophoretically. Over 500 of these restriction fragment length polymorphisms (RFLP) have been mapped to specific sites on all 20 soybean chromosomes. These RFLPs are used as reference points to map identified genes on individual chromosomes. In addition, the RFLPs are used to locate multiple sites on chromosomes that are associated with the expression of quantitatively inherited traits. Knowing the number and locations of sites controlling the expression of specific traits of soybean increases the efficiency of breeding for these traits. [*See* Plant Genetic Enhancement.]

A Genetic Type Collection for qualitatively inherited traits is a part of the soybean germplasm collection maintained by the USDA-ARS at Urbana, Illinois. The Genetic Type Collection includes strains that contain all published genes of soybean, a collection of near-isogenic lines containing various combinations of genes, a linkage collection containing combinations of linked genes, and a cytological collection containing interchanges, inversions, deficiencies, trisomics, and tetraploids of soybean. [*See* Plant Genetic Resources; Plant Genetic Resource Conservation and Utilization.]

Many economically important traits of soybean are controlled by genes with qualitative effects (Table I). The two major growth types of soybean, determinate (*dt1*) and indeterminate (*Dt1*), affect flower development and, indirectly, plant height. Genes affecting time of flowering and maturity, *E1–E4*, have been used in combination with alleles at the *Dt1* locus to develop cultivars uniquely adapted to specific production systems.

Reactions to major pathogens of soybean are controlled by genes with qualitative effects. Genes for resistance have been incorporated into improved soybean cultivars to minimize losses due to these pathogens. Several genes have been identified that affect chemical composition of soybean seed. Cultivars have

TABLE I

Genes Controlling Traits of Economic Importance in Soybean

Gene	Phenotype
	Growth and morphology
DT1	Indeterminate plant type
dt1	Determinate plant type
E1-E4	Time of flowering and plant maturity
	Pathogen resistance
Rpg1	Bacterial blight (*Pseudomonas syringea* pv. *glycinea*)
rxp	Bacterial pustule (*Xanthomonas campestris* pv. *glycines*)
Rcv	Cowpea chlorotic mottle virus
Rpv1, rpv2	Peanut mottle virus
Rsv1, rsv1-t, Rsv2	Soybean mosaic virus
Rmd	Powdery mildew (*Microsphaera diffusa*)
Rpm	Downy mildew (*Peronospora manshurica*)
Rcs1-Rcs3	Races of frogeye leafspot (*Cercospora sojina*)
Rpp1-Rpp3	Races of soybean rust (*Phakopsora pachyrhizi*)
Rbs1, Rbs2	Races of brown stem rot (*Phialophora gregata*)
Rps1-Rps7	Races of Phytophthora rot (*Phytophthora sojae*)
Rdc1, Rdc2	Races of stem canker (*Diaporthe phaseolorum* var. *caulivora*)
rhg1, rhg2, rhg3, Rhg4	Races of cyst nematode (*Heterodera glycines*)
	Variants for seed protein and oil
lx1-lx3	Absence of lipoxygenase enzymes Lx1, Lx2, Lx3
ti	Absence of Kunitz trypsin inhibitor
fan[1]	Low linolenic acid
fap1[2]	Low palmitic acid
fap2[2]	High palmitic acid
fas, fas^{a}, fas^{b}[3]	High stearic acid

Adapted with permission from Palmer, R. G., and Kilen, T. C. (1987). Qualitative genetics and cytogenetics. *In* "Soybeans: Improvement, Production, and Uses" (J. R. Wilcox, ed.) 2nd ed., pp. 125–209. ASA, CSSA, SSSA, Madison, WI.

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been developed that lack the lipoxygenase enzymes L2 and L3, resulting in improved flavor of oil and of soy food products. The cultivar "Kunitz," that lacks the Kunitz trypsin inhibitor, produces seed with improved protein digestibility that can be fed to finishing hogs without first preheating to inactivate this trypsin inhibitor. Cultivars with low linolenic acid have improved oil flavor and stability and those with altered levels of palmitic and stearic acids have potential use in specialty markets for soybean oil.

III. Quantitative Genetics

Most soybean traits of economic importance including seed yield, plant maturity, plant height, lodging resistance, seed size, and protein and oil content of the seed are quantitatively inherited. These traits are controlled by few to many genes and may be strongly influenced by environment.

Quantitatively inherited traits of soybean are controlled by genes with additive genetic effects. That is, the many individual genes that control the expression of these traits each have small effects that combine in an additive fashion to control the level of expression of a trait. Since soybean cultivars are true-breeding inbred lines, these additive effects can be fixed during the development of inbred lines and maintained in selections released as new cultivars.

A. Heritability of Traits

The degree of genetic control of a quantitatively inherited trait is frequently expressed as the heritability of that trait. Estimates of heritability are applicable only to the population from which they are derived. However, when different traits are measured in a single population, or in different populations, the relative heritability of the traits can be determined. Heritabilities for traits of economic importance and of primary interest to soybean breeders are shown in Table II. Seed yield, economically the most important trait of soybean, typically has a low heritability relative to other traits. In contrast, plant maturity, percentage seed protein, and percentage seed oil are traits that are highly heritable. Heritability estimates are used to predict progress that can be made by selecting for a specific trait in a breeding population. In general, greater genetic improvement results from selecting for a trait with a high heritability than when selecting for a trait with a low heritability.

B. Interrelationships Among Traits

Quantitatively inherited traits may be associated with each other to varying degrees depending upon the population in which these traits are segregating. Correlations between traits may be higher in segregating populations where parents differ greatly in measured traits than where small differences exist between parental values. Table III lists typical correlations between seed yield and other quantitatively inherited traits in soybean. In these populations there is no

TABLE II

Heritability Estimates in Percentage for Quantitatively Inherited Traits in Progenies from Different Soybean Crosses

Trait	Cross 1	Cross 2	Cross 3	Cross 4	Cross 5	Cross 6
Seed yield	38	23	10	39	52	58
Seed weight	68	53	44	92	92	88
Plant height	75	82	70	66	82	90
Lodging	54	59	51	60	63	70
Maturity	78	84	79	75	90	92
Seed protein	63	—	57	76	86	81
Seed oil	67	—	51	74	88	82

Adapted with permission from Burton, J. W. (1987). Quantitative genetics: Results relevant to soybean breeding. *In* "Soybeans: Improvement, Production, and Uses" (J. R. Wilcox, ed.), 2nd. ed. pp. 211–247. ASA, CSSA, SSSA, Madison, WI.

association between seed yield and oil content of the seed. In contrast, in most of these populations there is an inverse relationship between seed yield and seed protein content. This inverse relationship has limited progress in developing cultivars with superior seed yield and high seed protein.

Correlations among traits may simplify or complicate breeding efforts to develop inbred lines with specific combinations of traits. Soybean breeders may use selection indices when selecting for multiple, correlated traits. These selection indices are numeric values that put different emphasis on the selected traits and are usually based on heritability and economic value of the traits and on correlations among the traits.

IV. Sources of Genetic Variability

Genetic variability provides the basis for breeding improved cultivars; without variability there are no opportunities for genetic improvement. Genetic variability exists in germplasm collections and is created by making crosses among selected parents, followed by self-pollination to permit segregation for observable traits.

A. U.S. Soybean Germplasm Collection

The USDA-ARS maintains about 14,000 soybean accessions at Urbana, Illinois. These accessions have been collected from primary centers of origin for soybean, China, Japan, and Korea, and from other countries where soybean research has resulted in the development of diverse germplasm. The collection contains accessions of *Glycine sojae*, a wild, annual relative that has the same chromosome number and is cross-compatible with the cultivated soybean. There are accessions of 15 other perennial *Glycine* species that generally are not cross-compatible with the cultivated soybean without the use of special tech-

TABLE III

Estimates of Phenotypic Correlations of Seed Yield with Other Traits in Progenies from Six Soybean Crosses

Trait correlated with seed yield	Cross 1	Cross 2	Cross 3	Cross 4	Cross 5	Cross 6
Seed weight	−0.07	0.20	0.10	−0.01	0.21**	0.21
Plant height	0.32**	0.44**	−0.13	−0.04	0.02	0.26
Lodging	0.36**	0.27*	−0.21**	0.03	−0.20**	−0.26
Maturity	0.37**	0.37**	0.13	0.08	0.22**	0.37
Seed protein	—	−0.42**	0.22**	−0.34**	−0.17*	−0.14
Seed oil	—	0.05	−0.01	0.26	0.08	0.07

Adapted with permission from Burton, J. W. (1987). Quantitative genetics: Results relevant to soybean breeding. *In* "Soybeans: Improvement, Production, and Uses" (J. R. Wilcox, Ed.), 2nd ed., pp. 211–247. ASA, CSSA, SSSA, Madison, WI.

*, ** Exceeds the 5 and 1% probability levels, respectively.

niques to culture immature embryos from interspecific crosses.

The germplasm collection is an important reservoir of genes that has been essential to the development of improved cultivars. About 20 of these accessions have provided the germplasm for 95% of released cultivars. In addition, the germplasm collection has contributed genes for pathogen, nematode, and insect resistance that have been essential for successful soybean production in areas where these pests limit seed yields. The collection has also contributed genes for improved chemical composition of the seed that will increase both uses and markets for soybean. This collection is the ultimate source of genetic variability for soybean improvement.

B. Cultivars and Breeding Lines

Two commonly used sources of genetic variability for cultivar development are previously released cultivars and improved germplasm registered with the Crop Science Society of America. Descriptions of both registered cultivars and germplasm are published in the journal *Crop Science*. Registered germplasms may not merit release as cultivars but are genetically improved sources of unique traits.

Superior lines from various soybean improvement programs are an important source of genetic variability for soybean improvement. These lines may not possess all the attributes required for release as improved cultivars but have combinations of characteristics that make them useful as parents. Cooperative performance tests of superior breeding lines, conducted by soybean breeders, provide a method for exchange of this genetic material.

C. Transgenic Plants

The development of transgenic plants provides the opportunity to increase genetic variability for soybean beyond limits imposed by intra- and interspecific cross compatability. Current technology permits foreign DNA from totally unrelated species to be introduced and expressed in the soybean genome. At present, transgenes controlling tolerance to specific herbicides, resistance to insects, and increased methionine in seed proteins have been successfully incorporated into soybean. This technology provides opportunities to extensively increase genetic variability, particularly for qualitatively inherited traits of soybean.

V. Breeding Objectives for Soybean

A. Seed Yield

The primary breeding objective for soybean improvement programs has been high seed yield. Soybean is sold by weight or volume of seed; therefore, increasing seed production per unit area is essential in the development of an improved cultivar. Selection for seed yield in a breeding program is usually delayed until homogeneous, inbred lines are developed; this minimizes genetic variability within lines and maximizes genetic variability among lines. Since seed yield has a low heritability and is strongly influenced by environment, reliable estimates of the genetic potential for seed yield are determined by replicated performance trials at different locations and over several years. Seed yields of inbred lines that are greater than parental yields result from transgressive segregation where new gene combinations affecting seed yield accumulate in inbred lines that were not present in parent cultivars. Soybean breeders have increased the genetic potential for seed yield an average of 0.5 to 1.0% per year over the past 50 years.

B. Plant Maturity

Maturity date is an important attribute for improved soybean cultivars. Soybean cultivars begin their reproductive phase in response to varying lengths of the dark period. The date that cultivars flower strongly influences the date they mature; therefore, cultivars are adapted to specific bands of latitude where seasonal variation in length of the dark period is associated with growing season. Soybean germplasm is classified into 13 maturity groups, from 000 through *X*. The 000 germplasm lines are adapted as full-season lines in the higher latitudes; X germplasm lines are adapted to low latitudes in close proximity to the equator.

Germplasm used in breeding programs may include parents from diverse maturity groups, so selection for suitable maturity for a production area is essential. Since maturity is a highly heritable trait, selections can effectively be made on a single-plant basis in early segregating generations following a cross. Soybean breeders have developed productive cultivars in each of the maturity groups and have expanded the range of maturity groups to include 000 and X.

C. Plant Height

Selection has resulted in the development of cultivars that vary from about 0.75 to 1.00 m in mature plant height when grown in productive environments. In the higher latitudes of the midwestern United States or southern Argentina, indeterminate cultivars are grown to obtain adequate plant height for high seed yields. In the lower latitudes of the southern United States and South America, determinate cultivars are grown to limit plant height during the long growing season. A few determinate cultivars have been developed for production in the midwestern United States. These cultivars average 0.50 to 0.70 m in mature plant height and are typically seeded at 1.5 times the normal seeding rate to obtain high yields of these short-statured plants.

D. Lodging Resistance

Lodging, the tendency of plants to lean away from vertical growth, may limit plant photosynthesis during the growing season and interfere with harvest when plants are mature. Lodging tends to increase as plant population increases since individual plants are taller and have thinner stems when grown at high populations. Lodging resistance was not an important trait when cultivars were grown for fodder or as a green manure and older cultivars frequently lodged badly. Breeding efforts have been very successful in developing cultivars that are resistant to lodging and produce high seed yields at normal plant populations. Determinate cultivars developed for the Midwest are very resistant to lodging, even at high plant populations, because of their short stature.

E. Seed Size

Seed size, commonly expressed as weight/seed, receives only limited attention in most soybean breeding programs. Seed of currently grown cultivars range in size from about 100 to 200 mg/seed. Within this range there is little relationship between seed yield and seed size. Soybean genotypes with exceptionally large or exceptionally small seeds do not produce as high yields as cultivars with the normal range of seed size. Seed size may be an important attribute of soybean cultivars developed for specialty markets. Very small seed, 80 to 100 mg, is preferred for the production of natto, a fermented food product in which the integrity of the seed is partially maintained. Large-seeded cultivars, 180 to 250 mg, have traditionally been preferred for the production of tofu, a curd developed by precipitating proteins from soy milk.

F. Seed Oil Content

Soybean cultivars typically average 20 to 22% oil in the seed and this value has not changed appreciably in 50 years of soybean breeding. Since there is no close association between seed yield and oil content, soybean breeders have been able to successfully increase seed yield while maintaining high oil content. Cultivars have been developed with 23% oil, which is near the maximum value of accessions in the germplasm collection. Recent breeding efforts have altered the fatty acid composition of soybean oil, providing opportunities for developing cultivars with unique fatty acid composition for specialty markets for soy oil.

G. Seed Protein Content

Protein content of currently grown cultivars ranges from 39 to 41% and, like oil content, has not been increased in 50 years of soybean breeding. Accessions are available in the germplasm collection that contain 52% protein in the seed. The strong inverse relationship between protein and oil has precluded the development of soybean with both high protein and high oil (Fig. 1). Disincentives for breeding to increase seed protein in soybean are: (i) soybean is purchased on a weight or volume basis with no premium for chemical composition of the seed and (ii) the moderately strong inverse relationship between seed yield and seed protein.

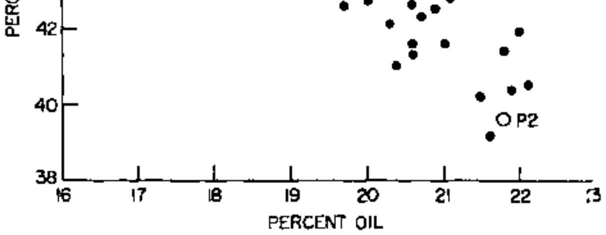

FIGURE 1 The inverse relationship between seed protein and oil content in progenies from a cross between "Pando" (P1) a high-protein parent and "Woodworth" (P2) a high-oil parent.

Increasing seed protein has recently become an important breeding objective to maintain the competitive place of U. S. soybean in world markets. Both recurrent selection and backcrossing breeding methods have been used to increase seed protein of breeding lines. However, in breeding populations the highest protein breeding lines generally are not the highest yielding lines. Backcrossing high seed protein into high yielding cultivars has been very successful in overcoming the inverse relationship between seed yield and protein. There has been virtually no success to date in overcoming the inverse relationship between seed protein and oil.

H. Disease Resistance

There are about 35 different pathogens that cumulatively cause annual losses estimated as high as 12% of the soybean crop in the United States. Some of these pathogens can be successfully controlled by the use of resistant cultivars. Breeding for resistance to specific pathogens that reduce seed yield or quality of seed produced is an integral part of most soybean improvement programs.

Bacterial diseases that reduce seed yield include bacterial blight (*Pseudomonas syringae* pv *glycinea*) and bacterial pustule (*Xanthomonas campestris* pv *glycines*). Selection for high seed yield and favorable agronomic traits has indirectly resulted in high levels of resistance to bacterial blight. Widely grown cultivars rarely show blight symptoms in breeding nurseries or production fields while accessions from the germplasm collection may show severe leaf blight when grown in these same areas. The *rxp* gene for resistance to bacterial pustule has been incorporated into virtually all cultivars grown in the southern United States, eliminating the 8 to 11% yield losses commonly associated with susceptibility to this disease.

Virus diseases for which genes for resistance are available include cowpea chlorotic mottle virus (*Rcv*), peanut mottle virus (*Rpv1* and *Rpv2*), and soybean mosaic virus (*Rsv1* and *Rsv1-t*). These virus diseases may reduce seed yield or cause discoloration of seed coats that reduce the value of the seed. Since economic losses due to virus diseases are not severe, breeding for resistance to viruses receives limited attention in most breeding programs.

Diseases caused by fungi cause the greatest yield losses in soybean and also are responsible for poor quality seed, resulting in lowered prices to the producer. Phytophthora root rot (*Phytophthora sojae*) can cause pre- and postemergence damping off of susceptible seedlings severe enough to require replanting of production fields. Damage may be as insidious as slightly reduced plant growth with subsequent losses in seed yield. This disease has been effectively controlled with the development of resistant cultivars. As new races of the pathogen became prevalent, additional genes for resistance were bred into new cultivars. Sources of field resistance, that are nonrace-specific, have been identified and are being bred into cultivars that will be resistant to a wide spectrum of races of the pathogen.

Brown stem rot (*Phialophora gregata*) causes internal browning of the pith and vascular tissue and foliar necrosis of susceptible cultivars. The disease is widespread in the midwestern United States and can result in yield losses as high as 44%. Several cultivars have been developed with moderately high levels of resistance to the pathogen.

Stem canker (*Diaporthe phaseolorum* var. *caulivora*) is characterized by a lesion encircling the base of soybean stems during early reproductive stages of the plant resulting in plant death. Virulent races of the pathogen have become prevalent in the southern United States causing yield losses as high as 100%. Resistant cultivars have been developed by incorporating into them one of two genes for resistance to the pathogen.

Sudden death syndrome (*Fusarium solani*) causes a foliar necrosis and eventual leaf loss as soybean enters the reproductive stages of development. The disease frequently occurs in production fields that have optimum growing conditions and high yield potential. Limited information is available on the genetics of resistance to the pathogen. Cultivars have been identified that have a high level of resistance and these are being used as parents to develop additional high yielding, resistant cultivars.

Soybean rust, caused by *Phakopsora pachyrhizi*, is a widespread foliar disease in the orient that can cause yield losses as high as 40 to 50%. The disease has not been identified in North America but has been found in Puerto Rico and South America. The disease can be controlled by the development of resistant cultivars, using the *Rpp1* and *Rpp2* genes.

Two pathogens adversely affect seed quality and result in lower prices for seed lots exhibiting disease symptoms. The *Diaporthe–Phomopsis* complex causes cracked, shrivelled, and moldy seed and reduces seed germination. Resistant accessions have been identified in the germplasm collection and have been used as parents to develop cultivars with a moderate level of resistance to the pathogen. Purple seed stain, a discoloration of soybean seed caused by *Cercospora* *kikuchii*, may be widespread in soybean producing areas under environmental conditions that favor the pathogen. Cultivars differ in susceptibility to this disease and soybean breeders select against extreme susceptibility, thus limiting disease problems under most production conditions. [*See* PLANT PATHOLOGY.]

I. Nematode Resistance

The soybean cyst nematode, SCN (*Heterodera glycines*), is the most destructive and widespread nematode attacking soybean. The minute worms feed on soybean roots causing extensive yield losses in southern, southeastern, and midwestern states of the United States and in China and Korea. Genes for resistance to specific races of the nematode have been incorporated into resistant cultivars using various breeding procedures. Each of these cultivars is resistant to a limited number of races of the nematode. The soybean accession PI 437654 is resistant to all known races of SCN and the resistance in this accession has been incorporated into the cultivar "Hartwig."

Root knot nematodes (*Meloidogyne* spp.), particularly *M. arenaria*, *M. incognita*, and *M. javanica*, can cause yield losses up to 90% on susceptible soybean grown in light-textured soils in warm climates. Nematode feeding results in galls up to 20 mm in size on plant roots, interfering with water and nutrient transport within the plant. Even though the genetics of resistance to root knot nematodes is not well understood, breeders have been successful in developing cultivars with high levels of resistance to this pest.

J. Insect Resistance

Foliar-feeding and pod-feeding insects reduce soybean yields more severely in the warmer climates of low latitudes than in cooler climates of higher latitudes. Identified resistance to insects has taken two forms, (i) antibiosis, an adverse effect of the plant on insect growth, survivial, and reproduction, and (ii) antixenosis, an adverse effect on insect behavior, such as visitation by insects. Antibiosis has been used in the development of cultivars with general resistance to foliar feeding insects. Antixenosis, in the form of dense pubescence covering the soybean plant, has been used to discourage both foliar- and pod-feeding insects.

VI. Breeding Methods Employed

Soybean breeding includes (i) creating genetic variability for specific traits, and (ii) identifying and selecting desireable variants for these traits. Breeding methods commonly employed in soybean improvement include pedigree, single seed descent, early generation testing, backcrossing, and recurrent selection. Each of these methods has been used to develop cultivars that have been released for commercial production.

A. Pedigree Method

The pedigree method has been used to combine favorable traits from two or more parents. Following a cross between selected parents, progenies are inbred from the F_1 through successive generations while maintaining the genetic relationship or pedigree of each selected individual. Several hundred F_2 plants are commonly grown from a cross and from these selections are made based on phenotypic attributes. Selected plants are grown in individual progeny rows in the F_3 generation and selections are made first among phenotypically desirable rows, and then for phenotypically desirable plants within rows. The process is repeated in successive generations, typically growing one generation each year in the field, until plants within rows are phenotypically uniform. Selected rows in advanced generations are harvested and evaluated in succeeding years in replicated performance trials. Advantages of the pedigree method of breeding are that selections can be made in early generations based on highly heritable phenotypic traits such as disease resistance, plant maturity, and morphological traits such as plant height. Breeding lines are evaluated in successive years under different environments, creating opportunities for the expression of traits and for effective selection. Typically one generation is grown per year so several years are required to identify lines for evaluation in replicated performance trials. This breeding method is not used extensively today but it was the primary soybean breeding method used until about 1970.

B. Single-Seed Descent

Single-seed descent, or a modification of this method, is currently the most commonly used breeding method to develop improved soybean cultivars. Following the F_1 generation from crosses between selected parents, the F_2 generation is grown and one seed from each F_2 plant is advanced to the next generation. The process is repeated, without selection, in successive generations until the desired level of inbreeding is attained, usually the F_4 or F_5 generation. Individual plants are then selected based on phenotypic traits and seed from these plants is increased to produce adequate seed for replicated performance trials. Since each F_2 plant is represented by a single F_4 or F_5 plant, genetic variability in the F_4 or F_5 generation is equal to the variability in the F_2 generation.

The single-seed descent method of breeding has several advantages in soybean improvement. Since no selection is practised in early generations and only one seed per plant is needed, several generations can be grown each year using winter nurseries or indoor growth facilities. Plants can be grown in very limited space and either photoperiod is controlled or growth regulators are used to minimize plant size since only one seed is needed from each plant. The primary disadvantage to this breeding method is that the identity of superior plants in each generation is lost. Therefore, superior F_2 and F_3 plants cannot be identified and additional selections made from progenies of these superior plants.

C. Early Generation Testing

Early generation testing is a breeding method designed to identify early in the breeding program soybean lines that have superior yield potential. The method utilizes evaluation of breeding lines in replicated performance trials during the development of inbred lines. Crosses are made between selected parents and the F_1 and F_2 generations grown as spaced plants to insure adequate seed production for performance tests. Initial performance tests are conducted in the F_3 generation evaluating F_3 lines from selected F_2 plants. Based on results of these tests, both crosses and F_2-derived lines with superior yield are identified and evaluated a second year in replicated F_4 performance trials conducted in multiple-row plots. F_4 plants selected from the border rows of these multiple-row plots are retained from those plots with superior performance. The F_4 plants from selected plots are evaluated as F_5 progeny rows, and then in the F_6 generation in replicated performance trials. The primary advantage of this breeding method is the identification in early generations of crosses and breeding lines that have superior yield potential. If superior F_2 lines can be identified early in the program, advanced generation selections can be made from progenies of these superior lines. This method requires extensive performance trials and data collection in all stages of the breeding program.

D. Backcrossing

Backcrossing is a widely used breeding method to transfer a specific trait identified in a donor parent to a recurrent parent that has superior attributes. A cross is made between the recurrent parent and the donor parent and as soon as progeny are identified that carry the desired trait from the donor parent, these progeny are crossed back to the recurrent parent. The process is repeated, using selected progeny from each backcross generation to again cross back to the recurrent parent until the phenotype of the recurrent parent is recovered, in addition to the trait transferred from the donor parent. Usually five to seven backcrosses are required to completely recover the phenotype of the recurrent parent. In each backcross generation progeny with the desired trait may be identified as early as the F_1 generation if the trait is dominant or in the F_2 generation if the trait is recessive.

Backcrossing has been used extensively in soybean breeding to incorporate specific genes for disease resistance into superior cultivars . For example, resistance to specific races of *Phytophthora sojae* have been incorporated into many soybean cultivars. When the resistant, backcross-derived form of the cultivar is released, the year of release of the resistant cultivar is appended to the name of the original cultivar, e.g., "Williams 82," "Century 84," and "Hobbit 87" are resistant forms of the cultivars Williams, Century, and Hobbit that were released in 1982, 1984, and 1987, respectively.

The advantage of the backcross breeding method is that success in cultivar improvement is assured. With an adequate number of backcrosses the phenotype and performance of the recurrent parent are recovered plus the desirable trait from the donor parent. The limitation of this breeding method is that no improvement is made for traits other than the one transferred from the donor parent.

E. Recurrent Selection

Recurrent selection, a breeding procedure more widely used with cross-pollinated crops, has been used successfully to improve soybean. This breeding procedure is used to improve quantitatively controlled traits by gradually accumulating in breeding lines genes that affect the expression of these traits. Selected parents are intermated in all combinations, and their F_1 progeny may be intermated to assure random assortment of genes controlling the desired trait. Progeny from the intermatings may be inbred one or two generations, and then evaluated in performance trials and a percentage of the best lines for the desired trait is selected. These selected lines are again intermated, either in all combinations or at random, to redistribute the genes controlling the trait. After performance trials, superior lines for the trait are again selected for the next cycle of intermating. The process is repeated for successive cycles. Recurrent selection has been used to accumulate genes affecting maturity, seed yield, and chemical composition of seed including oil, protein, and fatty acid composition of the oil.

The advantage of recurrent selection is that genes controlling quantitative traits can be effectively accumulated in breeding lines. Most traits of economic importance in soybean are controlled primarily by additive effects of genes and recurrent selection is effective in accumulating genes with additive effects. Selections can be made at any stage of a recurrent selection program, further evaluated in performance trials, and, if warranted, released as improved cultivars.

Recurrent selection requires extensive crossing among selected parents in each generation. Hand pollinations, which are difficult and time consuming to make, may limit the number of selections that can be intermated in each generation. Genes that cause male sterility in soybean have been incorporated into recurrent selection populations to facilitate intermating; selection to eliminate the genes for male-sterility is done during inbreeding to develop homozygous lines for release as cultivars.

VII. Performance Testing of Improved Germplasm

Soybean breeding lines, inbred to phenotypic uniformity, are evaluated in replicated performance trials to determine their merit for economically important, quantitatively inherited traits. These trials are conducted in multiple-row plots, 4 to 6 m in length, and replicated two to six times at a location. Multiple-row plots usually vary from 4 to 10 rows with spacing between rows from 0.75 m for 4-row plots to 0.20 m for 10-row plots. Only the center 2 to 6 rows are harvested to minimize effects of adjacent plots on yield determinations. Performance data, including maturity date, plant height, plant lodging, and seed yield are commonly recorded on these plots. In successive years of performance trials data may also be recorded on seed size and on protein and oil content of a sample of seed of each inbred line. Usually 10 to 15% of the superior lines identified in each years' performance trials are retained for evaluation in successive years of testing.

Initial performance trials are usually conducted at one location with two or three replications. Second- and third-year performance trials are conducted at more locations, usually two to four, and with three to four replications at each location. Economically important traits of soybean, particularly seed yield, are strongly influenced by environmental factors including temperature and rainfall that vary among years and locations. In soybean performance trials conducted at different locations and in different years, differences among years and among locations may be greater than differences among breeding lines. Therefore, soybean breeders conduct performance trials at multiple locations and years to identify breeding lines that can be expected to exhibit superior performance as improved cultivars.

In public breeding programs, superior breeding lines identified in state trials are entered into cooperative performance trials for each maturity group, 00 through VIII. These tests are conducted by soybean breeders and pathologists who grow the trials at multiple locations across the entire area of adaptation for each maturity group. Data are recorded on morphological traits, pest reactions, agronomic characteristics, and chemical composition of seed for each superior breeding line. These data are the basis for decisions as to which breeding lines merit release as improved cultivars. Individuals participating in these tests may use superior lines entered by any soybean breeder as parents in their breeding program. This policy promotes widespread use of superior breeding lines as parents for the development of improved cultivars. Commercial breeding programs conduct similar extensive performance trials of breeding lines at multiple locations across the area of adaptation of selected lines.

VIII. Increase and Distribution of New Cultivars

Soybean cultivars are maintained and distributed through seed certification programs with four classes of seed to maintain cultivar purity and identity. Breeder seed, produced and controlled by the breeder, consists of seed from individual plants of a cultivar that have been grown in progeny rows and selected for uniformity of phenotypic traits. In the United States, breeder seed may be produced from single plants only once, then maintained as a bulk seed lot. In many European countries, single plants are selected from a cultivar each year, their progeny evaluated for uniformity, and seed from uniform rows bulked to produce annual lots of breeder seed.

Foundation seed is initially produced from breeder seed and, in the USA, is maintained in successive generations by designated foundation seed organizations in each state. In Europe, foundation seed is usually produced each year from new lots of breeder seed.

Registered seed, produced from either breeder or foundation seed, and certified seed, produced from registered seed, may be produced by any grower interested in producing these classes of seed. Foundation, registered, and certified seed must be produced according to specific standards including field inspections of the cultivar during the growing season and inspections of harvested seed for genetic purity. Genetic purity standards for the three classes of certified seed are 99.9% for foundation seed, 99.75% for registered seed, and 99.0% for certified seed. In addition, seed of all classes must not contain more than 0.05% weed seed. Both registered and certified seed are sold to soybean growers for farm production of commercial soybean.

Comprehensive soybean breeding programs involve cooperative efforts of plant breeders with plant pathologists, nematologists, entomologists, and increasingly with molecular geneticists. Scientists in each of these disciplines contribute their expertise to the development of improved soybean cultivars. The development of an improved cultivar normally takes 7 to 10 years from the time a cross is made between selected parents until seed is available for farm production. In the first 2 years, inbred lines are developed that represent the variability available among progenies of a cross. The following 3 to 5 years are spent identifying inbred lines with superior attributes using replicated performance trials. Finally, about 3 years are required to increase seed of a new cultivar to amounts required for general farm production.

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Soybean Production

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Glossary

Bradyrhizobium Genus name of bacteria which are capable of establishing a symbiotic relationship with roots of legume plants; metabolic activity of the bacteria converts atmospheric nitrogen to a form useful to meet plant nutritional needs

Cation exchange capacity Capacity of soil to bond (with ionic forces) positively charged ions, which exist in equilibrium with the soil solution, which provides nutrients to the plant

Determinate growth Plant growth pattern which terminates vegetative development with the onset of flowering and seed production

Green manure crop Crop grown to improve soil, particularly in regards to nutrient supplying ability

Hectare Land area equal to 10,000 square meters, which is equal to 2.47 acres

Herbicide Chemical pesticide for control of weeds

Lodging Bending over or falling over by plant stems

pH Numerical value, ranging from 0 to 14, indicating the degree of acidity or alkalinity; a value of 7.0 is neutral, values <7 are acid and values >7 are alkaline

Photoperiodic response Response which occurs as a result of duration of the daylength

Shatter Splitting open of fruits (pods) on the plant, which results in dropping of seed or grain produced onto the ground

Variety (cultivar) Group of plants, within a species, which differ from the rest of the species because of their unique genetic composition

Vegetable oil Oil derived from plant tissues, chiefly from the seed or fruit portions of the plant

The soybean plant (*Glycine max* L.), a member of the Legume plant family, produces grain rich in both protein and edible oil. Because of its yield potential across a fairly wide geographic range, it provides large amounts of protein and oil required by the world's populations. With an annual life cycle, cultivated soybean is generally spring planted and matures before the onset of cold weather in the fall. As a member of the legume family, it converts atmospheric nitrogen to a plant useable form when proper strains of *Bradyrhizobium* bacteria are present in the root zone.

I. Introduction

The soybean evolved in southeastern Asia, where literature indicates its cultivation has been going on at least 3500 years in that area of the world. The soybean seed, or food products made directly from it, still constitutes a portion of the diet for many Asian populations. In western cultures, soybeans tend to be utilized indirectly through livestock, which consume the protein-rich meal made from the crop.

The soybean was brought to the western world on trading ships, arriving in North America in 1765. It was first grown in the area which is now Georgia. In 1851 soybeans were first introduced to Illinois, and within 3 years were disseminated to many midwestern farmers. Major increases in soybean production began during World War II, and acres grown in the United States reached a peak in the 1970s.

Early soybean use in the United States generally did not involve the harvest of grain, for it was grown for soil improvement (green manure) or for forage (hay or pasture) purposes. Because soybean production results in nitrogen fixation from the atmosphere, it provides nitrogen fertility which benefits the next crop produced. Since the introduction of soybean preceded the availability of commercial nitrogen fertilizer, its production was a means for farmers to enhance yields in crops responsive to nitrogen. The low cost of nitrogen fertilizer today generally does not make it economically viable for the soybean to be produced solely for its nitrogen contribution to the succeeding crop.

For seed harvest, early soybean production required a great deal of hand labor—making harvest as a cash grain impractical. Availability of the first grain combines, during the 1920s, made it feasible for farmers to produce the soybean as a grain crop. During this time a greater appreciation for the soybean protein and oil content also developed. Both of these stimulated interest in growing soybean for grain harvest.

Current soybean use in the United States and throughout the world is based primarily on grain protein and oil content. Livestock feeding consumes the majority of the protein meal produced from the grain, but many prepared foods often contain soybean flour, protein, or other grain components. Substitute or simulated meat products are produced from soybean protein as well.

Edible soybean oil is primarily consumed as cooking and salad oil, salad dressing, frying oil, and margarine. Because it has a very mild flavor, the oil is desirable for cooking purposes. Additionally, because of its relatively low level of fatty acid saturation, it is one of the most desirable oils for health conscious populations. Soybean is the major source of vegetable oil used in the United States today.

Alternative uses for soybean exist, but thus far have consumed only a small portion of the crop harvested. Nonfood uses of soybean include the manufacture of paints, adhesives, plastics, and inks. Soybean oil can also be used as an alternative, and renewable, fuel to power diesel engines.

A large portion of the soybeans produced in the United States are exported. World demand for protein and edible oil will only expand as the world's population grows, helping insure continued demand for the soybean. A summary of U.S. soybean production and export is shown in Table I.

TABLE I

U.S. Soybean Production and Exports, 1930–1991

	Thousand metric tons	
Year	Production	Exports
1930	381	0
1940	2123	0
1950	8138	762
1960	15,106	3674
1970	30,675	11,813
1980	48,938	19,706
1990	52,422	15,161

Major world soybean producers are the United States, China, Argentina, and Brazil. Argentina and Brazil are relatively new producers and exporters, having greatly expanded the scope of their production since the early 1980s. China, with its large population, consumes most of its production, leaving Argentina and Brazil as major competitors to U.S. farmers on the world market. South American competitors have the advantage of low priced land for expanded production, but are hindered by grain transportation to an export facility. Table II summarizes soybean production by the world's major producers.

II. Production Practices

A. Variety Selection

Selecting the best adapted varieties is basic to successful and profitable soybean production. Farmers need to use the most productive varieties with a maturity adapted to their area. In addition, other agronomic traits and disease resistance are criteria considered in choosing varieties. [*See* SOYBEAN GENETICS AND BREEDING.]

Soybean maturity is described by Maturity Groups, with Roman numerals used to designate the relative maturity. Earlier maturing soybeans, which require fewer days to reach maturity, are used at greater latitudes where the growing season is shorter. Later maturing varieties are used at latitudes closer to the equator. Thirteen Maturity Groups, from OOO (earliest) to X (latest) are used to describe soybean maturity. It is basically the photoperiodic (daylength) response effect on flower initiation in different varieties which makes them adapted to differing latitudes. For that reason, varieties cannot be moved very far north or south of their region of adaptation before they become too late, or early, in maturity. Figure 1 indicates the general areas of North America where different maturity groups are best adapted.

TABLE II

Soybean Production by Major World Growers

	1972	1982	1992
Country	(1000 metric tons produced)		
United States	34,921	60,697	53,892
Argentina	82	4137	10,479
Brazil	3674	12,793	18,508
China	6287	9009	9608

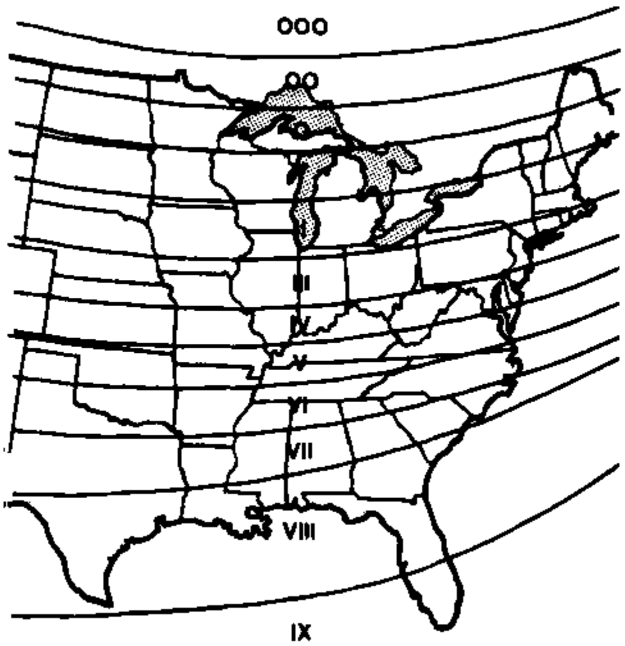

FIGURE 1 Distribution of Soybean Maturity Groups Adapted to North America. [Reprinted with permission from Scott, W. O., and Aldrich, S. R. (1983). "Modern Soybean Production." 2nd ed. S. & A. Publications, Inc., Champaign, IL.]

After farmers identify the Maturity Group(s) best adapted to their area, varieties with greatest yield potential and other desirable traits need to be identified. Many private seed companies have research programs which provide farmers with improved soybean varieties. In addition, land grant universities in soybean growing regions have variety development programs as well. Together, these two sources have released hundreds of new soybean varieties. Universities in soybean growing regions have variety testing programs which provide data useful to farmers as they select their soybeans.

Other varietal characteristics needing consideration include the ability of different varieties to resist lodging, as well as disease problems likely to appear in the farmer's fields. The ability of soybeans to stand well until harvested has been dramatically enhanced by plant breeding efforts. Resistance to several commonly occurring diseases, such as Phytophthora root rot (caused by *Phytophthora megasperma* (Drechs.) f. sp. *glycinea* Kuan and Erwin), brown stem rot (caused by *Phialophora gregata* (Allington and Chamberlain) W. Gams), and cyst nematodes (caused by *Heterodera glycines* Ichinohe), has been genetically incorporated into many varieties.

It is important for farmers not only to purchase the best varieties, but also to purchase quality seed of the most desirable varieties. Quality seed can be identified based on the germination score, vigor, and freedom from disease and mechanical damage to the seed. High germination levels and vigor will enhance the probability of a good stand emerging after planting. Freedom from seed-borne disease helps reduce infection of seedlings early in the season. Seed which are mechanically sound (not cracked or split) will have a greater percentage of undamaged seedling embryos within the seed. All these factors combine to enhance the probability of a good healthy stand of soybeans. Planting good quality seed does not guarantee a perfect stand, but without quality seed it is unlikely a good stand can be achieved.

An alternative to purchasing seed is to plant soybean seed which were harvested by the farmer the previous year. This is most likely to occur when the farmer is particularly pleased with a variety's yield and apparent seed quality. Because soybean is a self-pollinated species, varieties do not change genetically from generation to generation. Thus, it is possible for seed harvested one year to serve as planting seed for the next crop. The risk farmers face when using their own seed may be low quality, for exceptionally good management is needed to maintain quality. The advantage to farmers using their own seed is some economic savings.

B. Crop Rotations

Soybean yield tends to benefit from planting the crop in a rotational sequence, i.e., not planting soybean after soybean. Most soybeans are planted in fields which produced corn or some other grass crop during the previous year. Rotating crops in a field helps reduce pest problems, enhancing yield potential. Diseases that survive only on living soybean plants will be diminished in years when soybean is not produced. Planting crops such as corn, which differ considerably from soybean, allows the use of different herbicides for weed control as well. Weed management tends to be more effective when herbicide use varies with cropping seasons.

An additional benefit to soybean grown in rotation is a reduction in allelopathic effects from the previous soybean crop. Allelopathic effects, recognized only in recent years, can be described as a syndrome induced by chemicals released from decomposing crop residue, which has a yield limiting effect on that same crop when it is continuously grown. The greater the decomposition of crop residue, before a crop is planted again, the less damaging are allelopathic effects on that crop's growth and production. Crop rotation away from soybean allows greater decomposition of soybean crop residue, which reduces allelopathic effects which will be suffered by the next soybeans planted.

C. Seedbed Preparation for Planting

Tillage used for seedbed preparation varies greatly from farm to farm. All farmers do not have the same equipment for tillage and planting the crop, and soybean are grown on a wide range of soil types. These two factors combine to dictate the use of different tillage methods. Fields also have different topographic features, which relate to the potential for soil erosion. Concerns regarding soil erosion can greatly influence the type and amount of tillage most appropriate for preparing a field for soybean planting. The crop preceding soybean will also influence the amount of crop residue present in a field, which also determines tillage required to prepare a suitable seedbed for planting. [*See* TILLAGE SYSTEMS.]

Tools used to prepare fields for planting in various tillage systems include plows, disks, and field cultivators. Many farmers now use a chisel plow, in place of the traditional moldboard plow. Both the fuel required to accomplish needed tillage and greater crop residue remaining on the soil surface to control erosion favor use of the chisel plow.

The number of times the soil is worked with a disk, field cultivator, or other tillage tool after plowing is dependent on the extent to which the farmer desires to prepare a clean seedbed. Soil type, the extent of soil freezing and thawing during winter, and the level of crop residue help determine tillage needs for seedbed preparation.

Farmers are tending to reduce the amount of tillage done in their fields. As a result, more residue from the previously grown crop remains on the soil surface at planting time. This is an effective means to help protect and hold soil in place—reducing erosion potential from both wind and water. Planting equipment has been developed to allow soybean planting with considerable crop residue levels on the soil surface.

Many farmers view reduced tillage as a means to reduce the cost of producing soybean—for less time and equipment is needed for field work. As tillage is reduced, there is generally a greater need for herbicides to chemically control weed problems in the crop. A farming system which involves no tillage prior to planting is dependent on herbicides and some cultivation during the growing season to control weeds.

A final reason farmers are reducing tillage is that government support programs are not available to farmers who create excessive erosion problems with their farm operations. Farmers must be responsible for the potential erosion problems they generate, or they will not be entitled to government programs helping assure financial stability in farming.

Application of some herbicides can be combined with the use of a tillage tool such as a disk or field cultivator. Herbicide, sprayed immediately in front of the tillage tool, is incorporated at a shallow depth in the soil. Further incorporation of the herbicide, to insure uniform mixing, may be done with another tillage trip through the field prior to planting.

D. Soil Fertility—Mineral Nutrition

Soybean, as with all crops, depends on the soil to provide adequate mineral nutrition for normal growth and development. Nutrients most commonly supplied to soybean are phosphorus (P) and potassium (K). Each bushel of soybeans removes P contained in 386 g P_2O_5 and K contained in 590 g K_2O. For these, and other soil-derived nutrients to be available to roots, the soil pH level needs to be in the range of 6.0 to 6.5. Maintaining soil pH in this range benefits the activity level of the nitrogen fixing bacteria *Bradyrhizobium* as well.

Soil phosphorous and potassium levels must be maintained at recommended test levels to avoid nutritional stresses. Individual states have guidelines for maintaining soil test levels of P and K required to meet crop needs. Guidelines are based on soil fertility research, done in the differing soil types found across soybean producing areas. On soils with good cation exchange capacity, P and K can be applied before the year in which soybeans are grown. On soils with low or little capacity to retain applied P and K, more frequent applications are needed.

Liming, to raise the soil pH, should be done as needed with lime rates based on soil testing results. Between a pH of 6.0 and 7.0, soybean tends to optimize grain yields. Generally, maintaining a soil pH between 6.0 and 6.5 is most cost effective for farmers. Below a pH of 6.0, or above 7.0, mineral availability may become a yield limiting factor.

Because soybean fix nitrogen (N) with the assistance of *Bradyrhizobium* bacteria, nitrogen fertilizer is generally not applied. During early seedling growth, as the first two or three leaves develop, nitrogen fixation is initiated as *Bradyrhizobium* infect the soybean root. Small applications of N at planting time will often result in darker green seedlings, as nitrogen nutrition in plant tissues will be enhanced during early growth stages. Most positive effects of nitrogen applied at planting would be expected to be seen in sandy soils where irrigation is used.

Most areas producing soybeans have an established *Bradyrhizobium* population in the soil, because the bacteria can survive several years in the soil even if soybeans are not produced. Fields where soybeans have never been produced may lack needed populations of *Bradyrhizobium*, however. To insure the presence of the nitrogen-fixing bacteria, seed can be inoculated prior to planting. The bacteria, most frequently mixed into a ground peat carrier, is made to adhere to seed with a sugar-water solution, insuring the bacteria will be nearby the seedling as it becomes established. Alternative methods for introducing the needed *Bradyrhizobium* include granule and slurry products which are placed in the furrow with the seed at planting.

Several mineral nutrients are needed in very small amounts by soybean, but are just as essential as P and K to normal growth and production. Because of the small amounts taken up by the crop, those nutrients are typically called "micronutrients." Occasionally, a field may be found deficient. If not available in sufficient quantity from the soil, micronutrient deficiencies may be corrected with a nutrient spray application when deficiency symptoms become apparent. A small amount of the micronutrients can also be applied along with other fertilizer material if a deficiency is suspected based on previous crop growth or soil testing results.

E. Date of Seeding

In the northern hemisphere, the majority of soybeans are planted during the month of May. Delaying planting often results in reduced grain yield, and extreme planting delays will also put the crop at risk of fall frost damage. The impact which planting delays have on soybeans planted across the Corn Belt is presented in Table III. Penalties to yield are associated with delayed planting in southern latitudes of the United States as well.

TABLE III

Seeding Delay Effects on Soybean Yield in Central Corn Belt States

Seeding date	Percent yield potential
Early May	100 %
Mid May	100
Late May	95
Early June	90
Mid June	70
Late June	60

Soybeans in some areas are planted following the harvest of winter wheat or other small grain cereal crops which mature in early summer. This practice is referred to as double-cropping soybeans. A fairly small portion of soybeans grown in the Corn Belt are planted as double-crop, but in the southern and southeastern states, double-crop planting accounts for a considerable portion of total soybean acres planted. Table IV documents double-crop plantings in southern and southeastern states.

Planting dates used for soybeans in southern latitudes of the United States must consider photoperiodic (daylength) effects on the crop. Because soybean flowering is induced by exposure to a sufficiently short day, planting too early will induce premature flowering, which results in excessively short plants with reduced yield potential. Southern varieties are determinate in growth, and thus stop growing vegetatively when flowering begins. To avoid complications due to photoperiod effects, growers in southern latitudes of the United States generally plant the majority of their soybean during May, with some planted in late April and early June.

F. Planting Row Space

Most soybeans are planted in rows spaced 30 to 36 in. apart. A yield advantage is sometimes associated with row spacings more narrow, such as 7–10 in. Enhancement of yield in narrow rows can be ex-

TABLE IV

Double-Crop Planting of Soybeans in Selected States, Average of 1990–1992

State	Percent of acres seeded as double-crop
Illinois	4 %
Indiana	4
Kansas	2
Arkansas	31
Georgia	46
Kentucky	38
N. Carolina	30
S. Carolina	41

plained basically by greater sunlight energy interception by the crop canopy through the season.

Arranging a crop of soybean in narrow rows allows the canopy to fully intercept sunlight available by an earlier date in the season. Full interception of light earlier in the season allows a greater total amount of light to be intercepted by the canopy through the cropping season. Greater total light interception by a crop during the growing season can result in enhanced yield. Yield advantages associated with narrowed row spacing in soybeans tend to be larger in more northern latitudes than in southern regions.

While narrowed rows offer farmers greater yield opportunity, they may create both opportunities and challenges in regards to weed control. The plant canopy cover generated by narrow row plantings can help suppress weed growth by the shade imposed on weeds. At the same time, rows more narrow than 30 in. cannot generally be cultivated for weed control; thus, herbicides must be relied upon for weed control.

Narrow row soybeans, because they cover the soil with vegetation in fewer days, can also protect the soil from erosion. The plant canopy covers the area between rows, protecting the soil from the force of beating raindrops, which reduces the water erosion potential.

G. Plant Densities

Soybeans can maximize their yield potential across a rather wide range in plant densities. To a great extent, soybean can adjust or compensate for the population at which it is planted. Field studies evaluating plant density effects on soybean have indicated that stands of 300,000 to 370,000 plants per hectare are needed for optimum soybean yields. Across this range in plant densities, if plants are reasonably uniform in their distribution, soybeans tend to maximize their yield potential with timely planting.

Growing soybeans at insufficient plant densities encourages development of large branches low on the main stem. While branches produce grain, the position of these branches is not conducive to efficient mechanical harvest. Large branches attached low on the main stem may be laying on the soil at crop maturity. At harvest the combine may fail to collect grain if it is produced on branches positioned too close to the soil. At appropriate population ranges branches on the soybean tend to be fairly short, and emerge from the main stem well above the soil surface.

At excessively high plant densities, the soybean stem tends to be abnormally tall and structurally weak, which may allow the crop to lodge, causing harvest losses. In addition, soybeans which lodge during the grain filling period of development have a reduced ability to fill seed, due to reduced light distribution and photosynthesis in leaves.

Varieties with consistently short stems tend to stand better than average, and thus may be seeded at higher densities. Weak stemmed, or tall varieties, may need to be planted at slightly lower than average seeding rates, so that lodging can be avoided.

H. Pest Management

1. Weeds

In every soybean crop, weed management must be considered. Several approaches can be used to manage weeds—all intended to help reduce competition to the crop. In virtually every soybean field herbicide is used to manage weeds. In addition, mechanical control (tillage before planting and/or between row cultivation) is used in the majority of fields. Methods used for weed management depend on the type and density of weed problems, tillage systems used by the farmer, equipment available, and budgetary considerations. [*See* WEED SCIENCE.]

Herbicide options for soybeans are numerous, and change each year with new products and formulations available. Depending on chemical characteristics of the herbicide(s) used, application may be made during seedbed preparation, immediately after planting is completed, or after emergence of the crop and weeds. Farmers that use reduced or no-till production programs, and consequently do not have the opportunity to incorporate chemicals during seedbed preparation, must depend on herbicides which can be applied after planting or after the crop and weeds emerge. Those using narrow rows, which cannot be cultivated for weed control, are greatly dependent on herbicides suitable for application after planting or emergence of the crop. [*See* HERBICIDES AND HERBICIDE RESISTANCE.]

Herbicide selection for weed control needs to be based on weed problems anticipated in the field. Some herbicides provide effective control of grasses, but not broadleaf weeds, while others control broadleaf weeds but not grasses. A few help control both broadleaf and grass weeds.

In addition to considering weed species present, herbicide selection is influenced by cost of the product, time when application is needed, potential for soybean damage, carryover to future crops grown in the field, and environmental considerations. Newer herbicides tend to be most costly, but often provide weed control at a lower rate of chemical per acre. Reduced rates per acre are beneficial, since environmental concerns exist. Equipment available for application may influence the herbicide used, because different types of equipment are needed to apply herbicides at different times in the cropping year. Some herbicides are slow to breakdown or decompose in the environment, so they may potentially injure subsequent crops planted in the same field, or may create a greater risk to the environment. Applying herbicides properly, and at the proper time and rate, will minimize any potential danger or threat to both the crop and environment.

Mechanical weed control in soybean may be accomplished during seedbed preparation, as weed seed may be buried deep enough to prevent their germination. Also, early germinating weeds are destroyed by tillage. A rotary hoe, which is used soon after crop emergence, also is a form of mechanical weed control as it breaks up the upper soil layer and dislodges small weed seedlings.

Cultivation between rows for weed control is typically done once or twice in fields where preplant tillage was done and spacings between rows permit equipment operation. Cultivation can be done until the crop is large enough that row middles become filled with vegetation. In no-till planted fields, cultivation between rows is not done, which preserves the soil cover of crop residue.

2. Insects

At lower latitudes, with a longer growing season and milder winter, insects in soybean tend to be more of a problem. Various insects feed on different soybean plant parts—leaves, stems, roots, or developing grain. Sufficient insect damage can reduce the soybean's ability to yield. Minor feeding damage, however, may not result in detectable yield loss. Both the extent of damage and developmental stage of the soybean plant determine if control of insects present is warranted. Research on integrated pest management, which has been conducted in a farmer's area, is the best guide to understanding when insect control measures are economically justified.

Insect problems vary from year to year in regards to the specific insects present and the size of their populations. Weather plays a role in winter survival, reproduction rates, and distribution or movement of insects from field to field. Because insect problems are not always associated with soybean production, it is best to manage problems as they become apparent and threaten crop productivity. In addition to cost saving, it is more environmentally friendly to apply insecticides only when they can be justified.

3. Diseases

Disease problems can greatly limit soybean production potential. Disease incidence and severity are determined in large measure by local weather patterns. Some diseases may thrive under very humid or wet conditions, while others may tend to do best in hotter and dryer conditions. While the farmer cannot control weather, through variety selection management of several diseases may be accomplished.

Many varieties available to farmers now have genetic resistance to some diseases which are frequently encountered. Unfortunately, genetic resistance is not available for all diseases which can infect soybean. From those varieties adapted to their area, farmers must look for those which have disease resistance in addition to the yield and agronomic characters desired.

Cultural practices such as the use of disease-free seed, providing adequate soil fertility, and the use of crop rotations, will all help reduce disease incidence in soybeans. Use of disease-free seed may prevent a disease from being introduced to a field. Providing adequate fertility keeps plants more vigorous, and better able to tolerate the stresses of disease. Crop rotations, when adequate in duration, reduce pathogen numbers in a field if they need living soybean plants to survive and multiply.

Chemical control, in the form of a seed treatment, can be used to manage some disease problems which are seed-borne. Seed treatment may also be useful to manage diseases which are soil-borne and which often impact early seedling growth. Late season fungal-induced diseases which damage leaves can be managed with foliar sprays. The use of fungicides to control late season leaf diseases will only be profitable if the environment favors disease development, and if the crop is of relatively high value. Soybeans produced for planting seed purposes might be considered to have a relatively high value, compared to those grown for delivery to the grain market. [*See* FUNGICIDES.]

The soybean cyst nematode problem is often included in discussion of pathological problems of soybean. The cyst nematode, a microscopic round worm, causes root damage which stresses soybeans through reduced water and nutrient uptake, which in turn reduces yield. The cyst nematode problem has migrated across virtually the entire soybean growing region of the United States. [*See* PLANT PATHOLOGY.]

Management of the cyst nematode problem needs to include crop rotation and planting resistant varieties. The longer the time interval between susceptible soybean crops, the greater the number of cyst nematodes which die due to the lack of a suitable food supply. Planting a nonhost crop such as corn, followed by soybean variety resistant to cyst nematode, followed by another nonhost crop, tends to dramatically reduce cyst nematode populations in a field. Such a crop rotation will not eliminate the problem, but will reduce its severity to a level that a susceptible variety generally can be grown in the fourth year of the rotation. During the fourth year, the few remaining cyst nematodes increase in number, necessitating the start of another 4-year rotation cycle. Farmers using the 4-year rotation to manage their cyst nematode problems need to have cyst counts done on soil samples collected after the third year of the rotation—to insure populations have been adequately suppressed to allow production of a susceptible variety.

Varieties which are resistant to cyst nematode contain genes imparting resistance to specific races of the pest. Planting varieties resistant to a specific race(s) each time soybean is produced will encourage the increase in populations of nematode races to which varieties are not resistant, which then reduces soybean yield potential in the field. The 4-year rotation uses a susceptible variety in the fourth year. The purpose of planting the susceptible variety is to encourage a resurgence of nematodes for which genetic resistance is available.

4. Scouting and Pest Management

Scouting soybean fields, which is simply monitoring pest levels throughout the season on a regular basis, is the first step to control potential pests. Once a pest is identified, and the intensity or severity of the problem determined, the most appropriate and profitable course of action can be determined. The most profitable response to minor pest problems may be to do nothing, for treatment costs might exceed the value of potential crop damage. In contrast, higher levels of infestation may require immediate action to preserve crop profitability. To most effectively manage pest problems, soybean producers need to be aware of pests in their fields and their potential for damage.

I. Harvest

Once mature and sufficiently dry, soybeans are well suited to mechanical harvest with a combine. A primary consideration in harvesting soybeans is grain moisture level. Harvesting when grain moisture is in the range of 12 or 13% adds to harvest efficiency and helps maintain quality in the harvested crop. Soybeans are "toughest" at about 13% moisture; thus, they resist cracking and splitting at that moisture level, and pods thresh easily when grain is at 12 or 13%. Pods are not likely to shatter as plants are cut by the sickle of the combine at these moisture levels compared to lower levels. Moisture levels of 13% or less are also needed for safe storage of soybeans. If soybeans are above 13% moisture, drying of grain is needed for safe storage. Soybeans are sold on the basis of 13% moisture in grain, with higher moisture in the grain resulting in drying charges levied again the seller.

Soybean harvest equipment available influences the efficiency of this critical phase of soybean production. Some combine sickle bars may not follow the contour of the soil. If so, a portion of the soybean yield may escape the sickle bar and collection by the combine head. The better the sickle bar follows the soil contour, the greater the percentage of the crop that will be harvested.

Equipment adjustment and operation are critical to efficient harvest. Reel speed on the combine platform and forward travel speed both influence movement of the crop material into the head of the combine. Excessive reel speed causes shattering of pods; essentially threshing seed before they can be delivered inside the harvest equipment, resulting in harvest losses.

Internal adjustments of the combine need to be made based on the seed size and moisture content. Adjustments in the threshing cylinder may be needed based on soybean seed size. Cylinder speed needs to be adjusted to consider the "toughness" of pods, which is related to grain moisture at harvest. Cylinder speed needs to be fast enough to efficiently thresh seed from pods, yet not so fast that unnecessary cracking and splitting of grain occurs. Airflow within the combine needs to be adjusted so that chaff, dirt, and other crop debris is separated from the grain.

Estimates are that 2–3% soybean yield loss is typical during harvest, despite the farmer's best efforts. Losses are the total amount of crop which shatters from pods prior to combining, those lost in front of the grain head, cracks, splits, and unthreshed beans which remain in pods discarded out the rear of the combine.

III. U.S. Production and Utilization

A. Production Regions and Costs

Major soybean producing states in the United States are in the midwest. Illinois and Iowa have been major soybean producing states since it has been grown for grain harvest. In the past 10 years, Illinois and Iowa together have produced a third of the total U.S. crop (Table V). Production in other midwest states make major contributions to total U.S. production as well. Total production by the six states listed in Table V have averaged two-thirds of the total U.S. crop from 1984 to 1993. Highest yields per hectare have been achieved in Illinois, Iowa, and Indiana during that period.

States in the south and southeastern United States also produce soybeans, but both farm land devoted to the crop and yield per hectare are considerably lower than in the midwest. Yield per hectare tends to be relatively low in many southern areas for a number of reasons. The soybean is often planted after the harvest of small grains (double-cropped), which restricts yield potential. Due to chemical and physical characteristics, soils across much of the south and southeast tend to have lower productivity. In addition, insect and disease problems more frequently reduce yield of soybean in that region.

Total production costs per hectare for soybean vary across regions in the United States. All soybean production budgets include items such as seed, lime, and fertilizer charges, as well as machinery expenses and labor. Charges for land, pest management, and possibly irrigation, have a strong influence on the cost of production per unit of soybean produced in various areas of the United States.

TABLE V

Major Soybean Producing States, Average Total Production, and Yield per Hectare for the Period 1984–1993.

State	Total production metric tons	Average yield (kg/ha)
Illinois	9,310,908	2567
Iowa	8,498,472	2560
Indiana	4,622,244	2580
Minnesota	4,474,140	2231
Missouri	3,781,183	2056
Ohio	3,767,361	2466
U.S.	52,302,055	2197

Land, pest management, and irrigation costs vary greatly across areas producing soybean. Regardless of location, a major charge in a soybean production budget is for land. Land charges in the midwest tend to be highest, but highest yields per hectare are obtained in that region. Regardless of location, producers have to manage weeds, but may have other pests to manage as well. For weed control, virtually all soybean fields are treated at least once with herbicide. At lower latitudes, with warmer and longer growing seasons, management of insects is often needed and increases costs of production. Thus, total pest management costs are likely to be higher in southern regions. To reduce dry weather stress, some areas in the south or southeast are irrigated, which also adds to production costs.

Soybean yield per hectare, which varies greatly in the United States, does not always reflect the margin of profit made by the farmer. The total cost per unit of production determines whether soybean production is profitable. Total cost per unit soybean harvested tends to be higher in southern latitudes, because of actual expenses and yields harvested. The lack of profitability associated with soybean production in this region has resulted in many farmers reducing the farm area devoted to production in recent years. In contrast, farmers in the midwest enjoy higher yield potentials, and also have lower pest management costs, which tend to make production more profitable.

B. Protein and Oil Separation

Chemical components of cultivated soybean make it necessary that the grain be cooked before consumption by most animals. Raw soybeans contain trypsin inhibitors, which reduce digestion of protein in monogastric animals. Cooking the soybean destroys these inhibitors. Cooking of soybean is accomplished during processing, which is typically referred to as "crushing." The crushing sequence not only cooks soybean, but separates the oil and protein rich fractions in the grain. A bushel of soybeans yields a little over 11 lbs of oil and 47 lbs of protein-rich meal.

Soybean crushing begins with cracking the grain to loosen the hull (seedcoat) from the seed. Hulls are separated, while the balance of the grain proceeds to rollers which create thin flakes from the pieces of soybean. Hexane then flows through the soybean flakes, extracting the oil. Hexane is recovered from the hexane–oil mix, and is used again. Soybean meal, from which oil has been extracted, is then cooked to drive off the hexane remaining. Hexane is recovered from the cooking meal, and used again in the processing. Hulls removed at the start of processing are often recombined with the meal. If hulls are not remixed with the meal, protein level in the meal is higher.

Oil extracted from soybeans is refined to produce the vegetable oil needed for salad oil, shortening, margarine, and other edible oil items. Soybean meal, produced when oil is extracted from soybean, serves as a protein feed supplement for many livestock species. Protein levels in the meal vary with the soybean variety processed, and the degree to which hull material is recombined with the meal after oil extraction. Soybean meal typically has a protein content of 44%.

C. Consumption

The majority of the soybean crop produced in the United States is consumed by our food and feed industry, with the remainder available for export markets. Poultry and swine consume about 75% of the meal derived from the crop, with beef, dairy, and other livestock using smaller portions. Salad, cooking, baking, and frying oil account for roughly 80% of the soybean oil consumption in the United States. Manufacture of margarine consumes about 15% of the soybean oil in the United States. Table VI summarizes edible oil and fat consumption in the United States and indicates the relatively large role played by soybeans.

TABLE VI
Sources of Edible Fats and Oils for the United States and World, 1991

	Percent of total consumed by	
Source	U.S.	World
Soybean	74%	27%
Corn	8	[a]
Cottonseed	5	7
Coconut	1	5
Palm	1	20
Rapeseed	—	16
Sunflower	—	13
Others	11	12

[a] Included in other sources.

Industrial uses of soybean oil consumes a relatively small portion of that produced. In recent years, a soybean-based ink has become available, and is used to print many government documents, newspapers, and magazines. Using ink based on soybean oil, rather than petroleum, is viewed as an environmental advantage, as well as creating new markets and demand for the crop. The use of soybean oil as a liquid fuel, replacing or being mixed with diesel, is currently being developed. Because of air pollution concerns in major metropolitan areas, an expanding market for soybean oil used for fuel purposes is anticipated. Both the reduced particle emissions from soybean fuel and the renewable nature of the fuel make it a promising market for the soybean crop.

A material made from soybean meal and recycled newspapers has recently been developed, and in many instances may have the potential to replace wood. The material can be used in furniture, flooring, and paneling applications. Additional industrial applications to consume both soybean meal and oil will no doubt result as a consequence of research on soybean utilization.

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Structures

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Glossary

Confined animal housing systems (CAHS) Building systems to confine animals used for agricultural production and the associated electrical and mechanical systems associated with the production

Controlled environment agriculture (CEA) Industry that produces horticultural crops (primarily flowers and vegetables) within controlled environment structures (greenhouses, growth rooms, etc.)

Environment Word having two connotations: related to buildings it is generally taken to mean the environment inside buildings but is also used for exterior environment, as in natural settings surrounding a farmstead

Environmental stress Any situation in an organism's microenvironment that induces an adaptive response; a stress may be acute or chronic and adaptation to the stress may or may not occur; depending on type and level of environmental stress, the effect on the organism may or may not be negative

Environmental stressor Factor present in the microenvironment that induces environmental stress on an organism

Homeothermic Animals that maintain an approximately constant internal body temperature through a carefully regulated balance between the rate at which metabolic heat is produced and the rate at which it is dissipated

Indoor air quality Relatively subjective index used to describe how closely aerial conditions (combinations of humidity, dust, odors, vaporous contaminants, etc.) match the needs of the occupants

Lower critical temperature Effective environmental temperature at the lower end of an animal's zone of thermoneutrality

Mechanical ventilation Ventilation of a building using mechanical means, generally fans; in agricultural buildings which house animals or grow plants, fans are typically of the propeller type and ducts to distribute fresh air are not generally used; in product storage buildings fans may be of propeller or centrifugal type and ducts to distribute fresh air are commonly used

Microenvironment Combination of environmental factors in the immediate vicinity of an organism, including air temperature, relative humidity and other aerial constituents, light intensity and quality, air velocity and turbulence intensity, sound intensity and frequency, and all other environmental factors important to the organism

Natural ventilation Ventilation of a building using only passive means: thermal buoyancy and/or wind-induced pressures

Thermoneutrality The temperature at which a homeothermic organism is most comfortable and exhibits no behavioral response characteristic of heat or cold; neither vasodilation nor vasoconstriction dominates in blood vessels near the skin; piloerection for heat loss suppression and moisture evaporation for cooling from the skin or respiratory systems are minimized.

Upper critical temperature Effective environmental temperature at the upper end of an animal's zone of thermoneutrality

Agriculture comprises a complex industrial process and buildings used for agricultural production should be integrated into a total system that provides at least the following: (1) desirable conditions to the housed animals or plants and the workers involved with them, (2) high production capabilities, (3) labor and energy efficiency, (4) economic effectiveness, and (5) limited environmental impacts outside the building. Agricultural structures are designed to modify microenvironments. Environmental modification is important to reduce weather- and microenvironment-induced stresses on the animals or plants and, in the case of stored crops, provide conditions that promote long-term quality retention and a minimum of spoilage and loss. The modification may be as simple as providing a sun shade for cattle in a warm climate, or as complex as a totally controlled facility for raising and storing food crops in a (now being planned) lunar colony.

To a significant extent, the design of agricultural structures has evolved in response to social, esthetic, economic, and political forces as much as in response to scientific input. Although design of today's agricultural structures is based more firmly on engineering principles, all the nonscientific factors listed are likely to continue defining, in part, the future development of agricultural structures.

I. The Need for Agricultural Structures

Most agronomically important crops are grown outdoors. Agriculturally important animals are raised with little or no shelter throughout much of the world. However, continuous exposure to the vagaries of weather and climate can impose stresses that limit production, increase morbidity, enhance exposure to injury and predation, and may ultimately prove fatal. This is true for both plants and animals.

Modern agriculture is sufficiently competitive economically that avoidable production losses cannot be accepted. This has led to various systems to house animals and plants and ameliorate the microenvironments they experience. The evolutionary process has been a long one. Records show, for example, mica sheets were used to create crude greenhouses to produce out-of-season cucumbers for Roman emperors. From earliest times, caves (where available) were used to shelter animals during the worst weather. Confined animal housing systems and controlled environment agriculture have matured greatly since then. Today's fully automated poultry house for 30,000 (or more) laying hens, dairy barn for hundreds of milking cows, or multihectare, highly automated, tomato production greenhouse controlled by a computer are simply steps along the natural progression from yesterday's primitive environmentally modified facilities toward tomorrow's totally enclosed and automated food production facilities on earth and in lunar (and beyond) colonies.

Agricultural buildings are, in effect, industrial production facilities. The agricultural activity within a building can be represented as an interacting collection of biological and physical processes and material transformations. A factor that sets an agricultural building apart from typical industrial buildings is the relative importance of the biotic system housed by the agricultural building. True, a factory must be staffed by people (at least today, before robot-run factories are the rule) but the people have a relatively small effect on the building itself. In an agricultural building the biotic system strongly affects the environment within the building and the environment provided by the building is critical to the welfare and production of the biotic system housed within.

The specific needs to be met by animal housing, product storage buildings, and greenhouses have led engineers to develop unique structural design and construction techniques. Generally, construction must be simple to limit costs because relatively large floor areas must be covered, areas that encompass an economic activity having relatively low return per unit area (contrast the yearly income from a dairy barn to the yearly income from an electronics equipment manufacturer, for example, having the same floor area).

Agricultural buildings often are not subject to the same constraints of building and other codes imposed on structures for human occupancy. This has permitted greater freedom for design innovation. However, aerial conditions within agricultural structures (high humidity in greenhouses, organic acids, dust, and other air contaminants produced by animal wastes, as examples) impose severe restraints on the choice of materials that may be used. Wood has been the material of choice for most animal housing facilities. Wood is relatively inexpensive and not subject to the corrosion characteristic of iron and steel. Steel buildings have been used to house animals, but often specially coated structural members are needed to limit corrosion. As an extreme, exhaust ventilating fans in swine housing are likely to have fiberglass bodies to avoid the corrosion that can destroy a steel body within 6 months of operation. In greenhouses, the need for sunlight has restricted construction to use of a structural covering of plastic or glass over a lightweight frame of steel, aluminum, or wood.

II. Planning Agricultural Structures

Every building must ensure its occupants (animal and human) will not be exposed to risks due to the building's construction. Every state in the United States has a building code devised to assure such safety. Local governments may impose additional restrictions. Such codes usually require construction in compliance with specific standards, or in accord with accepted engineering practice. In addition, energy performance standards have been adopted by many state and local governments. These codes may or may not apply to agricultural buildings, depending on local interpretation. Many codes specifically exempt agricultural buildings from certain provisions, but exemptions are not uniform and neither are they uniformly interpreted. Thus, in any construction it is necessary to consult with local building officials and obtain the necessary permits.

Site planning is an important component of agricultural building design. Important considerations include: water drainage (surface and subsurface), vehicle access, equipment parking, internal traffic patterns, exposure to winds and the prevailing wind direction and speed, adequate separation from human living areas, access to fields, solar exposure, storage, appearance, pollution hazards (internal and external to the site), labor efficiency in the context of the entire operation, waste management, feed distribution, electric and other utilities, soil characteristics, topography, production volume, and expectations for future expansion (for example, some experts recommend to plan the site assuming the operation will eventually double in size).

Topography is important for drainage, solar exposure, and snow control. Surface drainage requires a slope of 2 to 6%. Terraces and diversion ditches are used to intercept surface water. Such intercepts are usually grassed to limit erosion, and mowed to facilitate movement of water. Subsurface drainage can be achieved by drain tiles and pipes and is necessary for all building foundations and below-grade structures. A south facing slope will enhance drying, which is a benefit after rains. Tree windbreaks or windbreak fences provide protection from both winter storms and drifting snow. Windbreaks slow the wind for 10 to 20 height equivalents downstream of the break and 5 to 10 upstream. Several rows of evergreen trees provide an excellent windbreak, but a constructed windbreak may be desired until trees grow to sufficient height. The constructed windbreak should not be solid—an 80% solid windbreak provides better wind and snow protection than does a solid one.

TABLE I

Recommended Floor Areas per Animal Used for Design of Confined Animal Housing Systems

Animal	Floor area, m^2/head
Swine	
Nursery pig	0.3
Growing pig	0.6
Finishing pig	0.8
Beef animal, confinement barn	
Cow/calf unit	4
To 250 kg	2
Over 250 kg	3
Dairy animal, total confinement	
Tie stalls	1.4 (W) × 1.8 m
Free stalls	1.2 (W) × 2.3 m
Sheep, ewes, w/solid floor broilers	
To 4 weeks of age	0.05
4 to 10 weeks of age	0.1
10 weeks to adult	0.2

Space requirements depend on the animals or plants being raised. Overcrowding causes animals to be stressed and perform poorly, and is likely to increase disease and injuries. As examples, recommended floor areas for some agriculturally important animals are listed in Table I.

III. Materials for Agricultural Structures

Agricultural buildings must be constructed to withstand four types of loads: dead, live, wind, and snow. Dead loads are vertical loads due to the weight of the construction materials and permanently installed equipment. Live loads are movable, such as equipment, animals, products, and stored materials. Design live loads are typically less in modern agricultural buildings than in public and commercial buildings. Wind loads may be horizontal or vertical (e.g., uplift) but do not include tornado winds. Snow loads are vertical loads applied to the horizontal projection of the roof.

Wood is frequently the construction material of choice. It is workable on the site, amenable to do-it-yourself construction, reasonably inexpensive, and retains its strength for a relatively long time in a fire. It also is subject to decay by fungi and damage by insects. Wood used for agricultural construction may be natural, or treated to resist decay. However, care is required in selecting the type of wood preservative, for volatile chemicals used in the preservative treatment may continue to evaporate and cause damage to plants if used in greenhouses, for example. Many new techniques are available to improve the strength to weight ratio of wood construction and use lumber that otherwise would be discarded. Use of laminated solid beams, box beams, and wooden I beams are three such techniques.

Concrete and masonry are commonly used for foundations, floor slabs, and walls. Air-entrained concrete is often recommended to resist weathering and the destructive actions of animal wastes. Slotted floors in animal housing are usually made of reinforced concrete slats.

Plastics have found several applications in agricultural building construction. The most obvious is foamed plastics used for insulation. Closed cell foam insulation is recommended in damp conditions. In addition, various plastic surface treatments have been used to improve the longevity and cleanability of walls and ceilings. Such surface treatments are typically integral with prefabricated panels. Rigid, clear plastic panels are available for greenhouse covering. The panels may be single layer, but numerous panels are now available having two plastic walls connected by internal webs that provide both strength and an air space for thermal insulation. One or two layers of plastic film (e.g., polyethylene) are also used extensively for low-cost greenhouse covering. Glass is, of course, widely used as a greenhouse covering.

Steel and aluminum have been widely used in agricultural buildings, for both framing and cover. Many storage buildings and farm shops, and some animal housing buildings, are mostly or all metal. Virtually all greenhouse framing is metal, in contrast to the extensive use of wood (e.g., cypress) in the past.

IV. Animal Housing

A. General

Confined animal agriculture has been characterized by several trends. One has been continued growth in the sizes of operations and the numbers of animals housed at single locations. Another is the trend away from combining animal housing and human housing at the same location—the "farmstead"—and a concomitant move toward more careful site planning. In fact, increased specialization has led to animal agriculture operations having no cropland base and where all feed must be purchased. A third trend is the growing involvement of third-party professionals in planning the production unit and selecting systems and components. A fourth is an increasing regulation for environmental reasons of animal and other wastes generated within the production unit.

The dominant development in animal housing during the past half century has been a long series of design modifications to increase animal housing density and deal with the resulting need for more precisely modulated environmental control. The poultry industry (especially the egg producing industry) has been the most evident example of increased housing density. Some swine facilities have also recently been designed and constructed to mimic the principles of laying hen confinement—confinement of the animals in cages that are stacked (spaced) vertically to increase space efficiency. Buildings having high animal densities are typically ventilated using mechanical ventilation. Simultaneously, primarily in the dairy industry, average herd sizes have increased to the point where stanchions/tie stalls are no longer labor efficient and free stall housing has emerged as the dominant housing method. Free stall housing is generally based on a large, open, naturally ventilated building where the air temperature remains close to that outdoors. Thus, we see change in two directions—one based on carefully controlled environment and active environmental modification, and one based on limited or no environmental control and passive environmental modification. [*See* DAIRY CATTLE PRODUCTION; POULTRY PRODUCTION; SWINE PRODUCTION.]

B. Mechanically Ventilated Animal Housing

Animal housing typically comprises a single air space, in contrast to industrial, commercial, and residential buildings for humans. This simultaneously simplifies and complicates the science and art of environmental control.

Mechanically ventilated housing generally corresponds to what is termed "warm housing" in which air temperature is maintained above freezing and often within a fairly narrow zone, when possible. Domestic animals are homeothermic with typical body temperatures of

Cattle: 38.5°C
Horses: 38°C
Sheep: 39°C
Goats: 40°C
Swine: 39°C
Chickens: 41.7°C

For comparison, human deep body temperature is 37°C.

A well-known relationship can be used to predict the rate at which warm-blooded animals generate body heat,

$$\text{Heat, watts per killogram body mass} = k\,(\text{body mass, kg})^{0.75},$$

where k is a constant that depends on body form. This relationship has been based primarily on adult animals in their natural habitats. Animals that are in the unnatural state of high production (growth, milk, eggs, etc.) can be expected to have a higher metabolic rate than predicted by standard values of k. The degree to which the standard values are exceeded depends on the degree of rapid growth and production. More accurate data may be found in engineering handbooks and the research literature.

The temperature range best for animals within a building is that which produces conditions of thermoneutrality, shown schematically in Fig. 1. The low temperature end of the thermoneutral zone is termed the lower critical temperature (LCT) and can be used as the lower limit of desired temperature for cold weather environmental control. The high temperature end is termed the upper critical temperature (UCT) and environmental control should endeavor not to exceed the UCT for more than short times during a day. Some evidence shows animals are able to compensate for short periods (several hours) above the UCT by, for example, taking advantage of night time coolness. In addition, animal management may be simplified by proper environmental modification that takes advantage of the lack of comfort below the LCT. For example, control of air flow and resulting temperature in a swine facility can create zones within pens below the LCT and zones above it. Pigs, being naturally clean animals, will then use the colder parts of the pens only as dunging areas and rest only in the warmer parts of the pen.

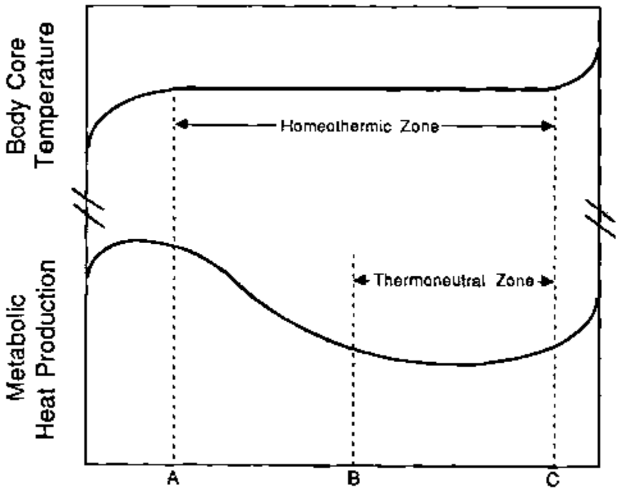

FIGURE 1 Body core temperature and metabolic heat production as functions of the effective environment temperature. To the left of A is the region of hypothermia and to the right of C is the region of hyperthermia. Between B and C, temperature regulation is by physical means and to the left of B increased heat loss to the environment can be compensated only by increased feed consumption and metabolism.

Temperature control of animal housing buildings to attain thermoneutral conditions is typically more effective during cold weather than during hot periods. Considerations of cost (installed and operating) limit the number of methods available in a practical sense for temperature control—refrigerated air conditioning, for example, is not used. The thermoneutral zone for mature animals is typically well below their deep body temperatures and is a factor that depends on their rate of production or growth, the feed characteristics (energy content) of their diet, the presence and amount of bedding, the thermal radiation balance of the animal, relative humidity, and air movement and turbulence intensity. In mechanically ventilated housing for mature animals, metabolically produced heat is often the only source of heat for the air space. Mature animals (with their greater body mass) produce more heat per unit area of housing space and usually exhibit a lower thermoneutral zone. When immature animals are housed, supplemental heat is often required.

Today's trend to greater animal housing density and genetic manipulation (breeding) to develop high-producing animals results in a great deal of heat production within the ventilated space. The amount of heat is typically sufficient to balance heat loss through the structural cover and ventilation and yet maintain air space temperature at or above the lower critical temperature unless the outdoor air temperature is extremely cold (e.g., below −20°C). On the other hand, the high heat production rate does not usually permit temperature control to within the thermoneutral region when outdoor air temperature is near or above the upper critical temperature. A maximum installed ventilation capacity of one complete air exchange per minute is typical in most mechanically ventilated animal housing, which limits the temperature rise of the ventilating air to perhaps 2°C, but in many regions of the world there are many hours of weather at or above the thermoneutral region. Evaporative cooling (either by cooling the air prior to its being introduced into the air space or by introducing a fine water mist within the air space) is the most typical means of environmental cooling. Evaporative cooling is most effective in dryer climates, but even in moderately humid climates there is some potential for its use during the hottest time of day when the relative humidity is usually at its lowest. The defining factor is the difference between the outdoor dry bulb and wet bulb temperatures (the so-called wet bulb depression). A well-maintained evaporative cooling system should be able to bring the cooled air to within 2°C of the wet bulb temperature, which is a rule that can be used to assess the possible benefits of evaporative cooling. Mechanical refrigeration is usually thought to be too expensive for environmental modification in animal housing, except perhaps in localized zones such as providing cooled air directed at the animal's head for inhalation.

Mechanical ventilation of animal housing can be one of three types, depending on the locations of the fans:

1. Negative pressure, where one or more fans exhaust air from the air space. Air pressure within the space is slightly below that of outdoors (ideally between 10 and 20 Pa difference). Fresh air is drawn into the building through planned inlets and some enters through the many small openings (air leaks) in the building shell—the so-called infiltration. This is the most typical arrangement for mechanical ventilation of animal housing.
2. Positive pressure, where one or more fans push fresh air into the air space (usually through some form of widely distributed inlet area). Air pressure within the space is slightly above that of outdoors. Air from the space is exhausted through planned outlets and exfiltration occurs through air leaks in the building shell.
3. Neutral pressure, where fans are at both the inlets and outlets and the net pressure within the air space is approximately the same as that outdoors, and air infiltration/exfiltration is minimized.

Most mechanically ventilated, negative pressure, animal buildings (usually rectangular in shape, perhaps 15 m wide and up to 100 m or more long) are designed to draw air across the shortest dimension of the air space. Fans are typically located on the more sheltered (leeward) side of the building and inlets (often essentially continuous) may be located on the opposite side or on both sides. An alternate location for the inlets is along the center line of the ceiling, with air drawn through an insulated plenum constructed within the attic space. This concept of ventilation (a short distance from inlet to exhaust) was developed to limit the temperature rise of the air as it passes through the air space. Recent innovations ("tunnel" ventilation) are based on the opposite. Air is drawn through the building in the long direction, which significantly increases air speed within the space. Higher air speeds and the resulting greater turbulence intensity are thought to increase animal and worker comfort during hot weather.

Two principles are important in design and control of mechanical ventilation systems. One is that the ventilation rate (volumetric rate of air flow) is determined almost exclusively by the fans. The second is that air distribution and its subsequent mixing within the air space are determined almost exclusively by the inlets. Inlets typically include movable baffles that automatically adjust to modulate the effective area of air flow and thereby the inlet air velocity and indoor to outdoor pressure difference. Ample air mixing results from adequate inlet air speed which results, in turn, from a sufficient pressure difference from inside the building to outside. Pressure differences in the range of 10 to 20 Pa are usually adequate, leading to inlet air speeds from 4 to 6 m per second. The standard Bernoulli equation of classical fluid mechanics can be used to relate air speed and pressure difference. Control of the total system is best accomplished by modulating the fans based on indoor air temperature (trying to keep within the thermoneutral region) and adjusting the inlets based on the indoor-to-outdoor air pressure difference.

Ventilation systems such as described above work best with air spaces that encompass few or no obstructions such as partial or complete walls, pens having high and solid sides, and massive feeding structures, as examples. Such obstructions lead to dead air zones and subsequent unhealthy conditions. The systems also work best when the building is constructed to have as little air leakage—infiltration—as possible. Air leaks act as unplanned and uncontrollable inlets and provide paths of ventilation that short circuit the planned ventilation system.

Fans may be speed controlled and modulated to vary the ventilation rate, or may be single speed and activated and deactivated in groups (staged) as the ventilation need changes. Energy efficiency is an important criterion in fan selection and efficiency data are often available from the manufacturer and from independent testing laboratories. However, efficient fans do not remain efficient if permitted to become dirty or misadjusted. Cleaning and adjusting at least twice yearly is often recommended because of the dusty and humid operating conditions in most animal housing.

C. Naturally Ventilated Animal Housing

Naturally ventilated animal housing exists as two types—so-called "cold" buildings and "modified-environment" buildings. Neither type attempts to maintain indoor conditions above the housed animals' lower critical temperature during cold weather. However, building construction and animal care expenses are generally less, compensating for the resulting increased feed intake. Conditions during warm weather are often superior to those in mechanically ventilated animal housing.

Cold buildings are lightly insulated, large, open structures having an open front or large ventilation openings on their two long walls, smaller ventilation openings along their roof ridge, and no attic spaces. The side wall ventilation openings may be partly closed during winter to limit chilling winds and blowing snow, but indoor air temperature generally remains no more than a few degrees above the outdoors. Because the air can be very cold the buildings are generally used only for large and mature animals—dairy or beef cattle, for example. Such animals do not suffer when conditions are well below their lower critical temperatures and simply eat more to compensate for the increased heat loss to their environment. There is seldom any true control of either air flow or temperature in naturally ventilated buildings. The roof may be insulated to suppress condensation on the underside of the roof during cold and clear nights and reduce radiant heat loads on the housed animals during midday in the summer.

Modified environment buildings are insulated to a greater extent but still rely on wind effects and thermal buoyancy for ventilation. Movable vent panels are opened and closed in response to indoor air temperature in an attempt to keep the buildings from freezing. This type of housing may be used for dairy and beef animals but also for (for example) dairy calves and heifers and finishing swine and gestating sows, which are not highly susceptible to cold temperatures.

A critical time for proper operation of naturally ventilated buildings is during cold and still weather. Ventilation must be in response to thermal buoyancy when there is no wind. If thermal buoyancy is to work, at least two elevations of openings must exist—one at the high point of the air space and one low. A vent along the ridge of the building is usually the high opening, and remains open year around. A cap over the ridge vent to prevent rain entry is usually detrimental in regions where winter snows are frequent, for the ridge cap acts as a snow fence to cause snow to be driven through the vent, possibly creating a snow drift inside the building. Roof slope is important to facilitate warm air movement toward the vent; a slope of 1:4 is the recommended minimum and 1:3 is often used. Because air moving toward the roof vent is the warmest and most humid in the building, roof insulation is typically used, not to conserve heat, but to limit condensation on the under side of the roof.

Natural ventilation is typically combined with free stall housing for dairy cattle. The animals are penned in groups and are free to wander between a feeding and a resting area. This system is best suited to herds of at least 80 animals, where the herd can be divided into four reasonably sized groups having similar milk production and thus similar nutrition needs. The animals are taken in groups two or three times a day to be milked in a separate milking parlor. Manure is typically handled by automatic scrapers and bedding is used only in the resting stalls, if at all. Permanent mats may be used instead to replace bedding, some forms of which have occasionally been implicated in the spread of mastitis.

Dairy calves are often housed in a very simple type of naturally ventilated structure—the calf hutch. Calves are very susceptible to disease and when housed closely together in a ventilated room can pass a variety of diseases among themselves. This led, approximately two decades ago, to using small (1.2 × 2.4 m × 1.2 m high) hutches (boxes) open on one end and with no floor, with the open end facing away from prevailing cold winds (and usually south for solar gain). The insides of the hutches are bedded, as with straw. Either there are small fenced spaces outside the open ends or calves are tethered to the hutches. The hutches are separated sufficiently that there is no calf-to-calf physical contact and hutches are moved between occupants to limit soil-borne transmission of diseases and parasites. Calves are placed into hutches within hours of birth, while they still retain the ability to produce brown adipose tissue (BAT, a form of body fat that is high in energy content and quickly available to the animal). Even in the coldest weather calves adapt well to this system, grow well, and show almost no morbidity. However, since the calves must be cared for daily, this has not proven the most popular system for farm workers (e.g., a natural reluctance to work outdoors to feed a group of calves during a blizzard) and thus a modification, based on housing calves in open-front sheds (usually facing south), has become popular.

The concept of the so-called "FLEX" house was first applied successfully in the poultry industry, and more recently to dairy housing. In concept, the FLEX house is a combination of a closed, mechanically ventilated building for winter operation and an open, naturally ventilated building for summer operation. Movable, but sealable, side wall vents are constructed, opened wide during warm weather, and closed except for a small, continuous inlet opening during cold weather. Fans are used only when the vents are closed. This form of housing takes the modified open front building concept one step further, permitting temperature control to within the animals' thermoneutral zone during cold weather, yet providing the advantages of natural ventilation during warm weather.

V. Greenhouses

Commercial greenhouses must serve several purposes. The paramount purpose is to provide stress-free environments to plants to encourage growth and development at rates that are optimally profitable. Concomitantly, efficiency of production, labor, and energy must be enabled. Plant growth may be in hydroponics, artificial media in containers, or soil (or raised soil beds), depending on the crop and grower preference. The trend is toward less growing in soil and more toward hydroponics (especially for greenhouse-grown vegetables). Growing plants hydroponically requires careful management of the nutrient solution to assure sufficient dissolved oxygen, and pH and nutrient control. An alternative gaining acceptance is aeroponics, which is a system in which the roots are sprayed with a fine mist of nutrient solution. Aeroponics assures adequate oxygen supply to plant roots. [*See* HORTICULTURAL GREENHOUSE ENGINEERING.]

Numerous regulatory pressures are forcing rapid changes in greenhouse site planning. Primary among these are regulations prohibiting discharges of water containing detectible amounts of the chemicals (fertilizers, growth regulators, pesticides, herbicides) used in the greenhouse industry, and other water pollutants. These discharges may arise from draining excess water used for watering plants (plants are often overwatered to prevent salts build up in the rooting medium), draining the condensate that forms during cold weather on the inside of the greenhouse cover, and even roof runoff, which carries with it contaminants from local and regional air pollution. Where regulatory pressures are greatest, "zero discharge" greenhouses may soon be required. In part these demands can be addressed by using ebb and flow systems or by capturing and recycling water used within the greenhouse, but site planning should also include an area for containing and treating large volumes of water, as from roof runoff. In addition, concerns for light pollution near residential areas may limit site selection options if night time plant lighting is planned.

Pollution problems are not confined to effects arising from the presence of the greenhouse operation. Water and air contaminants can have very negative effects on crop growth. Normal water contaminants such as calcium and magnesium that cause water "hardness" are not detrimental to plant growth. Less common contaminants such as boron are detrimental to certain plants. The background salts level in groundwater, if sufficiently concentrated (as may be the case in arid climates and near oceans, for example), may cause the total salts level to be too high after soluble fertilizer is added to the water, and be detrimental to plant growth. Air pollution can also negatively affect plants. For example, the presence of a nearby, heavily travelled highway may generate sufficient air pollution (NO_x, for example) to significantly reduce plant growth and perhaps even plant quality to the point where they cannot be sold.

Structural design loads that must be considered are generally the same type as with other buildings. However, the design snow load is typically less than for other building types because heat conducted from within a heated greenhouse is sufficient to melt snow nearly as quickly as it falls. In greenhouses constructed of many sections, joined at the eaves (gutter-connected), special heating pipes are placed under the joined eaves to melt snow and prevent its accumulation to a dangerous depth. Another difference in greenhouse design load assumptions is the type of live load that may be anticipated. Heating and ventilating equipment, hanging baskets of growing plants, carts for moving plants and materials that are suspended from tracks attached to the frame, and movable screens and curtains used for energy and light control may all be hung from a greenhouse frame. This has led to a recommendation that greenhouses be designed for a live load of 75 kg/m^2, the same as the recommended minimum design load for snow. Greenhouses are very light weight, making it doubly important that anchorage to the ground be able to resist the uplift forces generated by winds; a design wind speed of 35 m/sec (130 km/hr) is recommended.

Most greenhouses used for commercial production can be classified into six basic frame types, shown in Fig. 2. The hoop house is especially useful in the nursery industry for over-wintering plants and has also been widely used as an inexpensive structure for growing situations that last for only part of the year, such as growing bedding plants. The gutter-connected styles can cover many hectares under a single roof and usually form sections approximately as wide as they are long.

The greenhouse environment encompasses numerous environmental parameters. Greenhouse crop production must emphasize quantity, quality, and timing of product availability. Placing any of these three ahead of the others is difficult. The importance of timing is not as obvious as the other two, but flowers for holidays are worthless if late and vegetables that do not reach market at the contracted time may constitute a breach of contract. Plant growth in greenhouses is subject to the inconsistency of weather, especially solar insolation, and thus crop management is a highly refined skill.

Photosynthesis is driven by the light energy in the wavelength band from 390 to 700 nm. This wavelength band is the "photosynthetically active radiation," or PAR. Growth is little affected by where, within this band, the energy is received, although certain morphological developments depend on receiving some energy in specific parts of the spectrum (e.g., red or blue). Some plants adapt well to 24-hr lighting while other species require a dark period each day for proper development. Photoperiodism is exhibited relative to flower initiation in some species. Certain species are short day obligates (e.g., chrysanthemums), some are long day obligates (e.g., fuchsia), some are daylength-intermediate obligates, while others are day neutral.

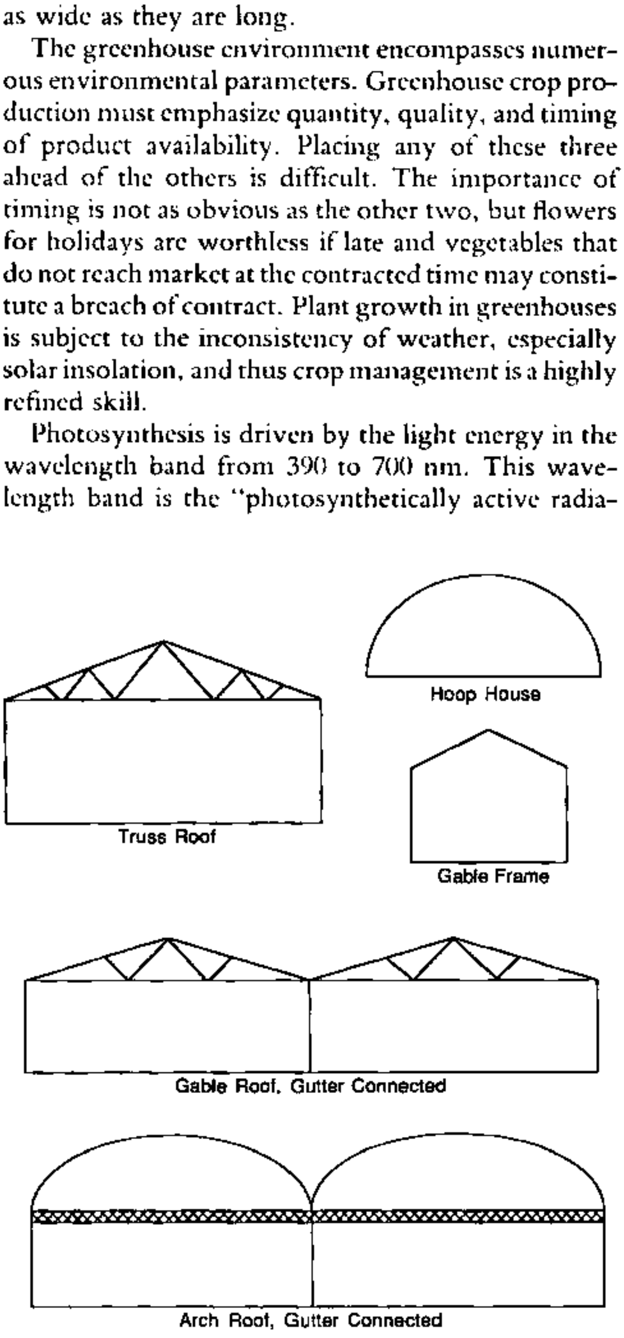

FIGURE 2 Six generic greenhouse frame types.

Supplemental greenhouse lighting for growth is generally accomplished using metal halide or high-pressure sodium luminaires. Uniformity of lighting is perhaps more critical for uniformity of plant growth than it is for lighting for human vision. The human eye responds logarithmically to light intensity and is thus insensitive to relatively large changes of the intensity. Plants respond essentially linearly to light; thus, a 10% variation of illumination can lead to a 10% variation of growth but be undetectable to the human eye. Supplemental greenhouse lighting for photoperiod control is often accomplished using incandescent lamps and relatively low light intensities, and light uniformity is not critical.

Temperature is another critical environmental parameter although its effects on plant growth are complex and not understood in fine detail. General practice is to heat to a specific night temperature (a blueprint condition determined by best plant response) and increase the day temperature 5 to 8°C above the night temperature. Space heating is often by hot water or steam, although forced hot air is also common. The crop may be heated using localized systems such as root zone (often provided by a warmed floor) or infrared heating systems, which require special controllers. Ventilation is by mechanical ventilation in most instances, although natural ventilation alone may be adequate in cool climate regions. Supplemental lighting and heating interact, for the lights emit infrared radiation which can heat the plant canopy several degrees above ambient air temperature.

Carbon dioxide is a nutrient required for photosynthesis. Whether supplementing carbon dioxide will provide additional plant growth depends, however, on whether it is the factor limiting growth at the time. If light levels are low, adding carbon dioxide will have little effect. If light levels are intense, inadequate access to carbon dioxide during the mid-day is likely to limit photosyntheses and thus supplementing can double plant growth rate. Unfortunately, frequently during the times when carbon dioxide supplementation would be most beneficial greenhouses are vented (mid-day, when solar intensity and the resulting heat load are greatest).

The carbon dioxide may be supplied from compressed gas or be in liquid form, or may be derived from exhaust gases from a natural gas or oil combustion unit (e.g., a central boiler) if care is taken to prevent incomplete combustion and the resulting ethylene (and other air pollutants) production. Special, high-efficiency burners are often recommended to limit introduction of harmful combustion products into greenhouses.

Ventilation system design in greenhouses must include consideration of air speed near the plants. If the air is stagnant, carbon dioxide can become locally depleted even while being added elsewhere in the greenhouse. Conversely, air speeds that are too high encourage excessive evapotranspiration, causing the leaf stomata to close and limit carbon dioxide uptake and thereby photosynthesis. As a general recommendation, air speeds of 0.1 to 0.2 m/sec are considered a good compromise. If areas of air stagnation are a problem, horizontal air flow and mixing can be added to a greenhouse. Horizontal air flow is induced by small (e.g., 0.4 m diameter) propellor fans spaced at even intervals around the greenhouse and directing air to flow in a racetrack pattern around the structure.

Because light environment is so critical to growth and quality of plant growth, especially during winter, the structural cover of a greenhouse should be highly transmissive to short-wave solar radiation. Greenhouse orientation also affects the light environment somewhat. A common recommendation is to have ridges of stand-alone greenhouses oriented east/west in northern zones (above approximately 35 N latitude, where the winter sun is low in the sky) to expose the largest possible greenhouse cover area for light interception during mid-day (when most of the sun's energy is received). Greenhouse ranges composed of gutter-connected units are recommended to have ridge lines oriented north/south so the shade lines of structural elements do not create zones of shade that move little during the middle of the day, retarding plant growth and development in those zones. In southern regions, stand-alone greenhouses are recommended to be oriented north/south to limit overheating during the day. Shade cloth is also used to reduce solar gain during the summer.

Greenhouses require a great deal of heating energy in cold climates. Because the light environment is so critical, normal insulation techniques do not apply. Double glazing the structural cover can reduce heat loss significantly, but the most effective insulation methods involve movable curtains deployed at night over the crop, creating an attic space under the greenhouse roof. Most greenhouse heating is required during the night (estimated to be approximately 70% of total heat needed in cold climates); thus, deployable insulation (thermal screens) can be reasonably effective even though they are stowed during the daylight hours. Advanced designs of thermal screens incorporate translucent materials and can double as shade cloth systems for crop protection during the heat of day during summer.

Greenhouse cooling is first accomplished by ventilation and then by evaporative cooling. Evaporative cooling may be produced by drawing ventilation air through wetted pads or by generating a very fine fog (mist) into the greenhouse. Evaporative cooling systems can provide cooling unless the outdoor relative humidity is very high. Mechanical refrigeration is prohibitively expensive for application in commercial CEA facilities.

VI. Product Storage

Drying and storing agricultural products requires specialized structures. In many cases these structures are purchased as whole units and are brought to the farm complete or in fabricated modules. Grains, especially, are harvested, dried, and then stored on the farm until use or sale. Drying is critical for preservation of grain and to prevent mold and fungi growth and grain spoilage. Certain fungi, if permitted to proliferate, produce compounds (mycotoxins) highly toxic to animals and humans. Drying typically reduces grain moisture content to 12 to 13%, on a wet basis. Some crops (e.g., oil seeds) must be dried to an even lower moisture content. Once dried, these crops can often be stored for several years with little deterioration. [*See* GRAIN, FEED, AND CROP STORAGE; POSTHARVEST PHYSIOLOGY.]

A very specialized form of storage has been developed, primarily for apples, although cabbage and celery also may be stored using the technology. The technology is controlled atmosphere (CA) storage. Storage in CA conditions reduces the respiration rate of the stored product by approximately half, extending storage life for apples, for example, by several months and making them available year around. The structure for CA storage is a tightly sealed and refrigerated building (or room) in which the atmospheric composition is carefully controlled. The oxygen content is lowered to a few percent (the exact value depending on the crop) and the carbon dioxide concentration is raised from ambient to several percent. This combination of actions greatly suppresses, but does not kill, the living organism which is the fruit or vegetable. The organism's metabolic rate is slowed sufficiently that respiration does not as rapidly consume the stored sugars, etc., in the product. When such food sources are depleted, the product dies and decay commences.

Extremely careful construction and control are required to construct and operate a CA storage and it is a technology not economically amenable to small-scale application. It is not unusual for several growers to cooperate to build, operate, and use in common a CA storage facility. Because of the modified atmosphere inside a CA storage, great care must be taken to avoid accidental suffocation by entering a CA room before it has been sufficiently purged with fresh air prior to removing the stored product and special life support equipment is required to enter such a room should some repair or other action be required before the storage would normally be opened.

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Sugarbeet

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Glossary

Biomass Dry matter produced by plants
Bolting Formation of seed stalks by the sugarbeet
C3 Photosynthetic system of most plants of temperate regions
EC European community
ET Evapotranspiration—the loss of water from a given area by evaporation from the soil surface and by transpiration from plants
Mg/ha (Megagrams per hectare) Similar to metric tons/ha; When multiplied by 0.446 equals short tons (2000 pounds) per acre
Petiole Stalk of a leaf
Photosynthesis Process by which green plants utilize the sun's energy to produce carbohydrate from carbon dioxide and water
Stand Number and distribution of plants after emergence from seed
Sucrose $C_{12}H_{22}O_{11}$, the sugar of world commerce
Ton Two thousand pounds, when multiplied by 1.102 equals one metric ton (Mg)

Sugarbeet and sugarcane produce nearly all of the world's supply of sucrose, the "sugar" of commerce. A crop of the temperate regions, sugarbeet is intensively farmed and is one of the most efficient plants used in the production of food for humankind and animals.

I. Classification, Origin, Adaptation, and Production

Sucrose is synthesized in most plants as a temporary storage product for photosynthetically reduced carbon, and is the most common form of carbon translocated in plants. Most plants convert photosynthate to starch for long-term storage. However, sucrose accumulates to an exceptional degree in two species, sugarbeet (*Beta vulgaris* L.) and sugarcane (*Saccharum officianarum* L.), which together form the basis for greater than 90% of the world's sugar trade. The sucrose derived from these two species represents approximately 11% of the world's food supply, and 0.2% of all the carbon fixed via photosynthesis by the world's crops each year. The most recent estimate for world sugar (sucrose) production is 114.3 million tons, of which one-third is derived from sugarbeet, and two-thirds from sugarcane. [*See* SUGARCANE.]

A genus of the family Chenopodiaceae, sugarbeet is one of a diverse and useful group of cultivars from the same species that includes swiss chard, fodderbeet, and red beet. The first modern sugarbeets originated as selections made in the middle of the 18th century from fodderbeets grown in then German Silesia, but food and medicinal uses of the genus are much older. A precursor is known to have been used as food as early as dynastic times in ancient Egypt. In 1747 a German chemist, Andreas Marggraf, demonstrated that the crystals formed after a crude extraction from pulverized beet roots were identical in all properties with sugarcane crystals, and attempts to derive sugar from beets originate from his work. His student, Karl Achard, developed processing methods for sugar extraction from the beet, and made the first selections

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† Deceased.

of higher sugar type beets. The blockade of shipments of cane sugar to Europe by the British during the Napoleonic wars stimulated a more intensive search for sweeter beets, a plant breeding program, and the construction of many crude factories in France and elsewhere to produce sugar from the sugarbeet. After Waterloo and the lifting of the British blockade, the incipient sugarbeet industry in France declined but the modern sugarbeet had been created and the efficacy of sugar extraction from beet had been demonstrated. The first successful commercial factory in the United States was constructed by E. H. Dyer at Alvarado, California, in 1879. Soon after, sugarbeet culture and factories expanded in many states. In 1917 there were 91 factories opening in 18 states. However, by 1989 there were only 36 operating factories in 13 states processing sugarbeet grown on about 550,000 ha. The major sugarbeet producing states in the United States are California, Colorado, Idaho, Nebraska, North Dakota, Minnesota, Michigan, Texas, and Wyoming.

Sugarbeet is grown predominantly in regions with temperate, Mediterranean, or arid climates. For the most part, beet-producing regions lie north and south of the 30th parallels. Sugarcane production is confined to tropical and subtropical zones. Table I contains data for sugarbeet production in the major beet-producing regions of the world. All of these regions except the EC, China, and Turkey also must import sugar from sugarcane-producing countries to meet a portion of their sugar demand. Sugar consumption has been growing at roughly the same rate as world population or 2% per year. There are substantial differences in per capita sugar consumption among nations. In part these differences are cultural, but per capita consumption also is correlated with wealth and is highest in Europe and lowest in China and Africa.

II. Industry Organization

Beet sugar production worldwide often is vertically integrated. Companies that process sugar from the beet root have considerable influence over all aspects of production from the area planted through the sale of the final product. The crop is of little value without a processor to extract the sugar, and once a sugar factory is constructed, a company must have a reliable supply of beets. Usually, there is a closer and more cooperative relationship among growers and companies than is found with other agronomic commodities. In the United States, the crop is grown most often under contract between the individual grower and a processing company. The contract specifies the area that can be grown, various details concerning the delivery of beet roots, and the method on which payment to the grower will be based. Typically, contracts guarantee the grower a share of the return the processor realizes from the sale of sugar. They often contain quality incentives. Sugarbeet growers, through the formation of local associations, influence the terms of the contract and inspect company operations, such as the method of sampling delivered sugarbeet methods of sucrose analysis and tare determinations. In the United States, sugarbeet processors and grower associations band together to influence national policy and legislation concerning the growing of sugarbeet.

In both Europe and the United States, sugarbeet variety improvement and seed production are carried

TABLE I

Sugarbeet Land Area, Root Yield, and Percentage Sugar Recovered for the World's Important Production Regions[a]

Region	Area planted (1000 ha)	Beet yield (Mg/ha)	% Sugar recovered	Sugar yield (Mg/ha)	Ratio of domestic production to consumption[b]
European Community[c]	1966	49.4	16.2	7.98	123
Eastern European Nations[d]	1055	32.5	12.5	4.05	(Not available)
Former Soviet Union	3150	22.8	10.4	2.38	60
United States	564	45.8	13.6	6.24	82
China	740	22.1	10.5	2.3	106
Japan	72	55.6	18.0	10.0	35
Turkey	391	37.7	12.8	4.8	103

[a] Three-year average (1990–1992). USDA-Foreign Agricultural Service. Sugarbeets are also grown in countries other than those listed, but the area planted is generally small.

[b] All sugar sources. China and the United States also produce sugarcane.

[c] Belgium-Luxembourg, Denmark, France, Germany, Italy, The Netherlands, Spain, and the United Kingdom.

[d] The former Czechoslovakia, Hungary, Poland, Romania, the former Yugoslavia, and the Baltic States: Estonia, Latvia, and Lithuania.

TABLE II

Approximate Water Use Efficiency (WUE) and Nitrogen Use Efficiency (NUE) of Various Crops Grown at Davis, California, Compared on Biomass, Harvested Yield, and Human-Digestible Energy Basis

Crop or product	Season Et (mm)	Biomass (kg ha^{-1})	WUE_b (kg ha^{-1} mm^{-1})	HI	WUE_h (kg ha^{-1} mm^{-1})	WUE_f (MJ ha^{-1} mm^{-1})	NUE_f (MJ ha^{-1} kg^{-1} N)
Corn	710	22,000	32.6	0.5	16.3	203	765
corn → milk	—	—	—	—	—	96	—
Barley	390	10,000	25.6	0.4	11.5	136	—
barley → beef	—	—	—	—	—	22	—
Dry bean	570	6,000	10.5	0.4	4.2	50	—
Sugarbeet	780	20,000	25.6	0.4	11.5	180	1810

Note. WUE_b, water use efficiency per unit biomass; WUE_h, water use efficiency per unit harvested biomass; WUE_f, water use efficiency per unit digestible energy; NUE_f, nitrogen use efficiency per unit digestible energy. Typical ET and biomass values based in part on Loomis and Wallinga (1991). Alfalfa: efficient or inefficient user of water? [*In* "Proceedings, 21st California Alfalfa Symposium, Davis, CA" (S. Mueller, ed.). NUE calculations based on Hills *et al.* (1983). Fertilizer nitrogen utilization by corn, tomato, and sugarbeet. *Agron. J.* **75**, 423–426.]

out primarily by private companies. However, the USDA developed most of the varieties grown in the first half of the 20th century in the United States and current variety development often uses genetic lines derived from USDA research. Most countries have variety testing programs to assure the use of cultivars that are productive and well adapted.

III. Growth and Development of the Sugarbeet Crop

The sugarbeet is a remarkable plant. A rapidly growing crop is capable of high rates of sucrose accumulation. California has regions which are ideally suited to commercial sugarbeet production. The world's commercial record has come from a field in the Salinas Valley and equalled 19.0 Mg ha^{-1} of sucrose from a crop grown over a 240-day period (115 Mg ha^{-1} of roots at 16.5% sucrose). Averaged over the total period of growth, the crop accumulated 185 kg total dry matter ha^{-1} day^{-1} (44.7 Mg total DM/240 days) and 80 kg sucrose ha^{-1} day^{-1}. Sucrose accumulation is not uniform throughout the growing season. Initially it is relatively slow. Peak sucrose accumulation rates are considerably higher than the average reported for a cropping season and likely exceed rates of 100 kg sucrose ha^{-1} day^{-1}. More typical crops reach half the biomass and sugar yields of record crops. An average hectare of sugarbeet in California produces 56 Mg of roots containing 15% sucrose. Upon processing, the beets yield 7.4 Mg of recoverable sugar, 3.4 Mg of dry root pulp, and 98 kg of monosodium glutamate, an amino acid salt used to enhance the flavor of foods. The sugarbeet pulp left after sucrose extraction is used widely in the dairy and beef cattle industries as a feed supplement due to its highly digestible fiber and energy content. Another 6.7 Mg dry matter of beet tops may be left in the field to fertilize subsequent crops or used as feed for cattle or sheep. When the beets are harvested, approximately 150 kg N, 20 kg P, and 150 kg K ha^{-1} are removed with them. These amounts of nutrients are roughly similar to those removed by a 10 Mg ha^{-1} crop of corn grain. Because beets are efficient at accumulating photosynthate in a useful form, they are also efficient convertors of agricultural inputs such as water and nitrogen (Table II). One of the reasons sugarbeet requires relatively low use of fertilizer nitrogen is its efficiency in recovering residual soil nitrogen from previous crops or decomposed organic matter. [*See* NITROGEN CYCLING.]

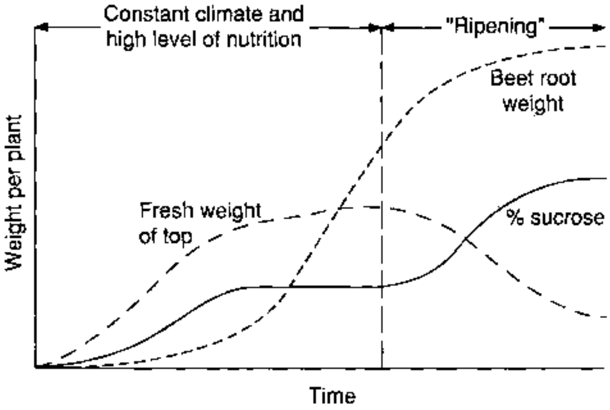

FIGURE 1 Schematic representation of growth of the sugarbeet. In a constant, favorable climate, vegetative growth continues indefinitely (Fig. 2). An increase in the sucrose concentration of the beet root is dependent on external factors, principally cool night temperatures and nitrogen deficiency (Courtesy of Albert Ulrich).

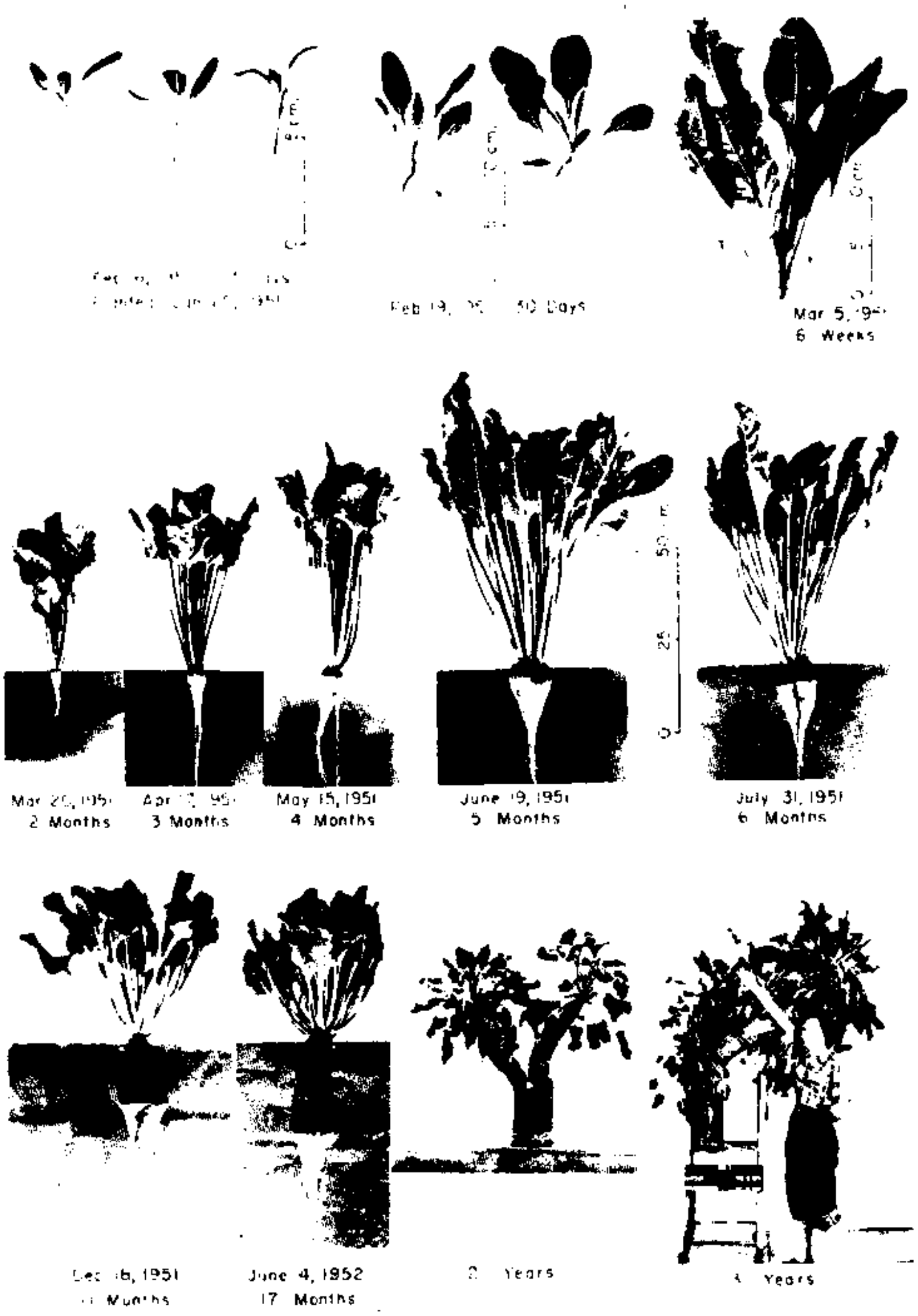

FIGURE 2 Growth and development of sugarbeets grown for 3 years with a plentiful nutrient supply in a climate favorable to vegetative growth. Bolting (seed stalk production) will not occur until induced by cold temperature (Courtesy of Albert Ulrich).

Figure 1 illustrates the growth and development of a sugarbeet plant. Under such appropriate conditions, the plant develops quickly from seed with the seedling emerging from the soil as soon as 5 days after planting. The taproot grows rapidly and may reach 30 cm or more by the time the first true leaf is developed. During the first 30 days, growth is confined primarily to leaves and fibrous roots. After about 30 days both top and storage-root growth proceed rapidly with tops reaching near maximum fresh weight in 60 to 90 days. Subsequently, with favorable climate, top growth remains fairly constant but storage roots con-

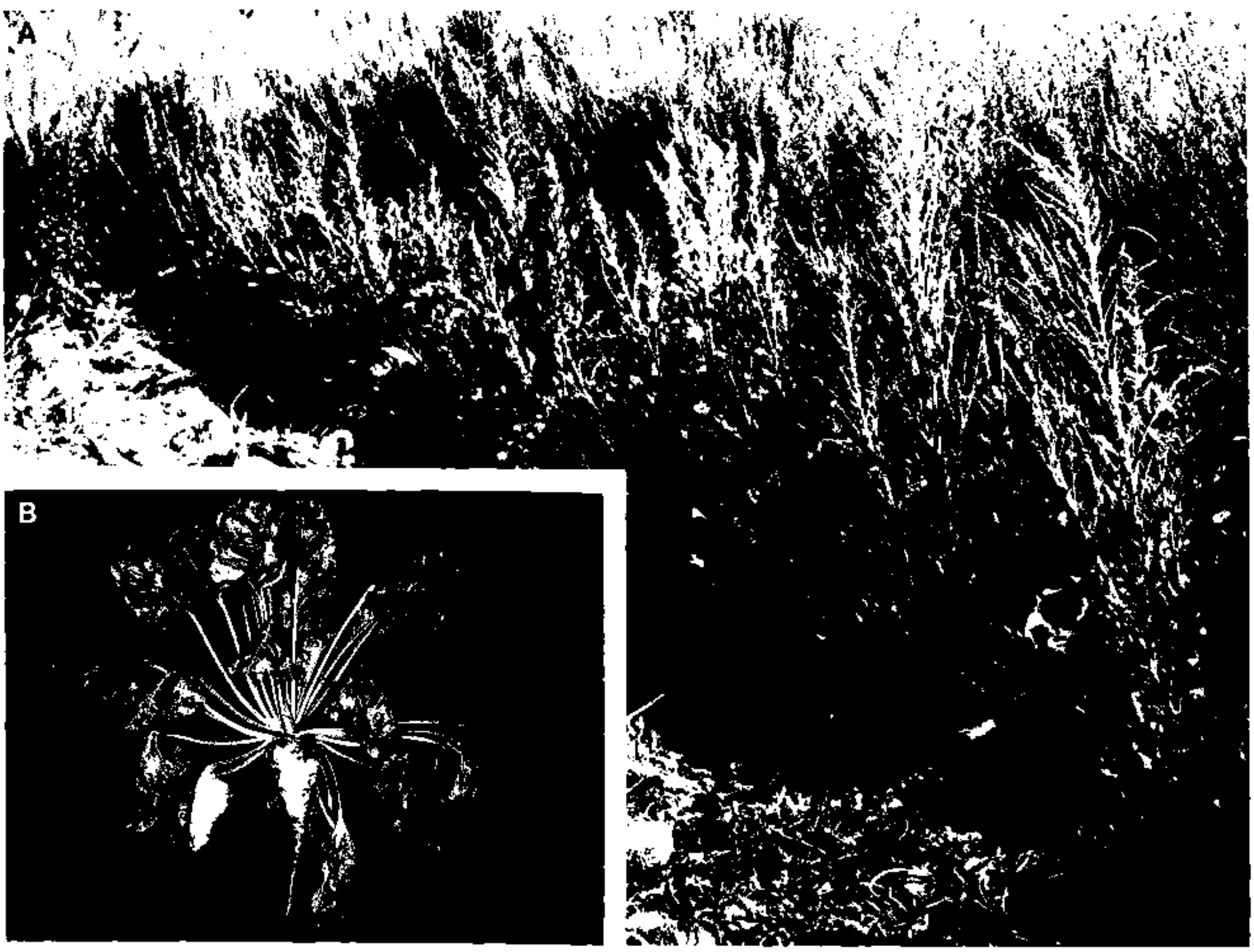

FIGURE 3 (A) The sugarbeet grows from 6 to 10 months before it is harvested for the sugar (sucrose) in its root. (B) Bolting sugarbeets. Seed stalks are induced by a period of cold temperature.

tinue to grow rapidly for another 20 to 24 weeks. Beyond that period, crown (stem) growth constitutes an increasingly larger percentage of the commercial storage root. As the storage root increases in size, there is a constant translocation of sucrose from the leaves to the root where it stored primarily in concentric rings of vascular tissue derived from secondary cambium initiated early in the root's development and in root parenchyma cells that enlarge during growth. On a fresh weight basis, the sucrose content of the root remains relatively constant until suitable external factors cause the concentration to increase. A rapid increase in root sucrose content is correlated with cool night temperatures in the fall of the year coupled with a nitrogen deficiency. Both of these conditions slow vegetative growth, particularly top growth, and the photosynthetically produced sucrose accumulates in roots as storage rather than as new vegetative growth. Figure 2 shows sugarbeet plants at various stages of growth over a 3-year period in a constant, favorable climate. Sugarbeet is a biennial and when the growing plant (Fig. 3A) undergoes prolonged exposure to cold tempeatures (approximately 90 days at 5 to 7°C) followed by warmer temperatures and longer day lengths, seed stalk production ("bolting") takes place (Fig. 3B). In the United States, sugarbeet seed is produced most efficiently in the Willamette Valley of Oregon, where winter temperatures are low but the roots do not freeze, allowing seed producers to manipulate the plant's biennial habit.

Most sugarbeet varieties currently grown are monogerm hybrids that out-yield older, open-pollinated types by from 10 to 20%. The use of monogerm seed, discovered by V. F. Savitsky in the late 1940s, eliminates seed balls with multiple embryos and crowding of seedlings when plants emerge. In turn, this improves the operation of mechanical thinners or eases thinning by long-handled hoes, and makes it easier to plant directly to a stand. Before planting, seed is processed and graded to permit precision planting, and is treated to protect germinating seedlings from soil fungi and insects.

IV. Management Practices and Production Problems

In most sugarbeet growing regions, the earlier the planting and longer the growing season, the higher the yield, provided that temperatures at planting are conducive to rapid growth and plants are not retarded by diseases or other problems.

Seeds are planted in rows from 50 to 76 cm apart. Within a row plants should be spaced at least 13 cm apart. Closer spacings tend to encourage vegetative growth at the expense of sugar yield. When plants are too far apart or spacings uneven, sugar yield is lost as well. Where conditions are conducive to good field emergence (50% or better) seeds can be planted 10 to 15 cm apart with the expectation that the resulting stand will not need to be thinned. Many fields, however, are planted at closer seed spacings and, with good emergence, require the use of mechanical or hand thinning to space the plants from 13 to 30 cm within the row. Good stands of sugarbeet planted in rows 50 cm apart contain from about 154,000 to 67,000 plants per hectare.

Generally, nitrogen fertilization is required for profitable sugarbeet production. However, sugar yield is sensitive to the timing of nitrogen availability, requiring ample amounts early for maximum vegetative growth but also a period of nitrogen deficiency prior to harvest for proper sugar accumulation in the storage roots. Figure 4 shows a typical response of a sugarbeet crop to fertilizer nitrogen. Highest sugar yields, a function of root yield and sucrose concentration, usually are achieved with a fertilizer rate that nearly maximizes root yield. However, this rate can be considerably less than the rate required for maximum total biomass production (roots plus tops) and usually is not the rate giving the highest root sucrose concentration. Data in Figure 4 indicate that application of 112 kg fertilizer N/ha resulted in maximum sugar yield and maximized profit to the grower. In this instance, plant analyses indicated that the crop was deficient in nitrogen for about 8 weeks prior to harvest. [*See* FERTILIZER MANAGEMENT AND TECHNOLOGY.]

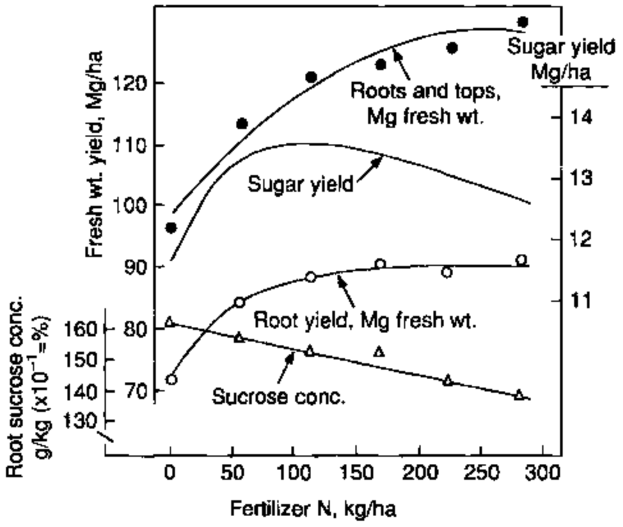

FIGURE 4 Response of sugarbeet to fertilizer nitrogen. Maximum sugar yield is produced at the N rate that nearly maximizes root yield (112 kg N ha^{-1} in this case), but far less than the N rate that maximizes total crop yield (roots + tops).

Sugarbeet can serve as a nitrogen scavenging crop to prevent possible nitrate pollution of groundwater. The crop has been shown to require from 25 to 50% less fertilizer nitrogen than corn (*Zea mays* L.) and when fertilized to produce maximum sugar per hectare recovers from fertile soil 2.5 to 3.5 times the amount of nitrogen applied as fertilizer. Sugarbeet tops, when returned to the soil, can reduce by 50% the amount of fertilizer nitrogen required for a following wheat crop under California conditions. The analysis of sugarbeet petiole (leaf stalk) samples collected in a systematic program can prevent the under- and overuse of fertilizer nitrogen.

Sugarbeet is a C3 plant with broad, dark green, succulent leaves. In arid areas of the temperate zone it must be irrigated. Careful and timely irrigations are essential to a good sugarbeet yield. Either furrow or sprinkler irrigation is possible. Sprinkler irrigation, though more costly, has the advantages of improving seedling emergence and using less water in the early stages of plant growth. Irrigation water requirements range from as little as 600 mm of water per hectare per season in a cool climate where the soil is filled with plentiful winter rain to as much as 1200 mm per hectare in a hot, dry climate with limited precipitation. [*See* IRRIGATION ENGINEERING, FARM PRACTICES, METHODS, AND SYSTEMS.]

Controlling pests and diseases is important for profitable crop production. Sugarbeet should not be planted in fields heavily infested with weeds. Moderate weed infestation is controlled by crop rotation and a combination of chemical and mechanical methods. Sugarbeet is susceptible to preemergence and post-emergence seedling rots known collectively as the damping-off diseases. Other important diseases which must be controlled in areas where they occur are: curly top, a virus disease transmitted by the sugarbeet leafhopper; sugarbeet yellows, a virus complex transmitted primarily though not exclusively by the green peach aphid; powdery mildew (*Erisphe polygoni* DC) and Cercospora leafspot (*Cercospora beticola* Sacc.), diseases caused by leaf fungi; rhizomania, caused by a virus (beet necrotic yellow vein) transmitted by a soil-borne fungus (*Polymyxya betae* Keskin); and the sugarbeet cyst nematode (*Heterodera schachtii* Schmidt) and root-knot nematodes (*Meloidogyne* sp.). Strategies for the control of these diseases involve development of resistant varieties, attention to time of planting, isolation of new plantings from old sugarbeet fields that can serve as sources of virus inoculum, the selective use of fungicides, soil fumigation, and careful attention to crop rotation.

V. Future Prospects

The land area planted to sugarbeet, and the sugar yields achieved in most of the principal beet-producing countries have remained stable or increased only slightly over the last decade or more. However, planting has expanded rapidly in China during the last several years as that country seeks to increase its domestic sugar production. Beet and sugar yields have increased in the northern European countries in the last several years (Table III). In the United States, yields have not changed significantly for over a decade. Stable sugarbeet yields over the last decade in the industrialized nations with intensive agriculture suggest that a yield plateau has been reached with the crop. Long-term trends for yield and sucrose percentage for California are depicted in Fig. 5. They reflect the successes and problems of modern, intensive cropping throughout the 20th century. Curly top virus was the first major challenge that struck the industry in the 1920s. Starting with the decade of the 1930s, yields began to increase and reached a peak in the early 1950s. Yields then stagnated or declined due to problems associated with the yellows virus complex. When these were diagnosed and a management program based on isolation was introduced in the late 1960s, yields rose once again as overall management improved, input use intensified, and superior varieties were developed and planted. However, yields have remained relatively stable during the last two decades.

There is potential for yields to improve significantly in some regions of the world. Those achieved in the Soviet Union are lower than in Poland and other eastern European countries with comparable climates, while those of eastern Europe are lower than yields achieved in comparable regions of western Europe.

TABLE III

Yield Trends in Selected Countries with an Industrialized Agriculture (Mg/ha)

	France		Germany		Netherlands		Great Britain		United States		Japan	
Year	Beet yield	Sugar yield	Beet yield	Sugar yield	Beet yield	Sugar yield	Beet yield	Sugar yield	Beet yield	Sugar yield	Beet yield	Sugar yield
1992/93	53.0	9.40	48.5	7.72	56.9	9.35	46.5	7.85	44.4	6.4	54.0	9.51
1991/92	53.6	9.76	49.0	7.54	58.5	9.24	46.2	7.82	45.0	6.05	57.2	10.83
1990/91	53.8	9.99	44.2	6.72	69.7	10.73	41.7	7.08	44.8	6.28	55.5	9.72
1989/90	56.0	9.85	44.2	6.71	56.3	9.70	41.2	6.81	43.5	6.00	50.9	9.26
1988/89	59.0	10.17	39.8	6.13	54.3	8.73	41.2	7.16	42.8	5.86	53.5	9.79
1987/88	53.6	8.81	44.3	6.20	53.2	8.39	39.8	6.64	50.2	6.84	53.9	9.58
1986/87	50.8	8.81	42.1	6.96	55.8	9.59	40.2	7.09	47.4	6.88	53.6	9.51
1985/86	51.2	9.26	43.4	6.53	48.4	7.44	38.0	6.51	45.8	6.08	54.5	8.79
1984/85	53.0	8.50	45.2	5.89	53.9	7.87	43.4	7.30	45.2	5.95	53.9	8.67
1983/84	48.6	5.07	44.7	5.20	44.3	6.57	40.8	5.89	44.6	6.03	46.3	6.99
1982/83	55.1	8.01	43.6	6.15	59.3	9.16	49.5	7.63	45.6	5.87	58.7	9.57
1981/80	54.1	6.69	34.3	6.06	56.9	8.72	35.4	5.68	50.3	6.06	45.3	7.26
Mean	53.5	8.69	43.6	6.48	55.6	8.79	42.0	6.96	45.8	6.19	53.1	9.12
SE	0.76	0.43	1.1	0.21	1.76	0.32	1.13	0.2	0.69	0.1	1.13	0.31
CV%	4.9	4.7	8.7	5.0	11.0	5.2	9.3	5.4	5.2	5.0	7.4	6.9

Source. USDA-Foreign Agriculture Service (1992).

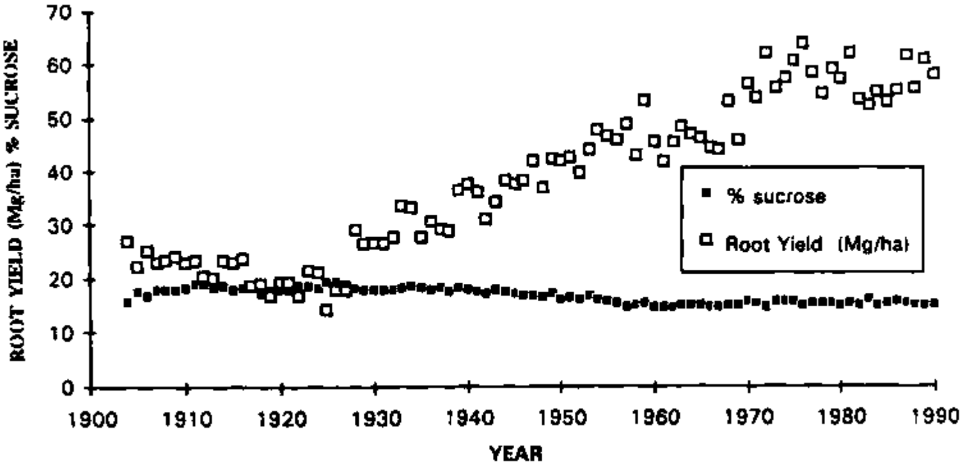

FIGURE 5 Trends for long-term sugarbeet yield and sucrose percentage in California (1904–1990).

Likewise, yields in China are much lower than those of Japan. These differences suggest that there is undeveloped yield potential in these large beet-producing regions, as well as room for improvement in extraction technology.

Just as sugarbeet owes something of its modern development to international conflict, so its future production may depend in part on the nature of international trade agreements. At times, the world has experienced a sugar surplus. In 1992, production is expected to exceed demand by approximately 0.7%. Some countries are more dependent on sugar production for their trade than others, Cuba (a sugarcane producer) being the most striking example. While sugar production is less important in nations that produce sugarbeet, the crop has an important biological role in crop rotations and an important economic role in providing income to farmers. This is especially true in the European Community. Also, established industries representing significant capital investment have been developed to process the beets into sugar. Sugar is a basic commodity and some nations would prefer not to become dependent on imports for their entire domestic supply. The cost of growing and processing sugarbeet in the industrialized world is higher on average than equivalent costs for sugarcane. This is due in part to differences in labor and other costs, and the value of assets devoted to crop production in the industrialized and developing nations. It is unclear how trade issues affecting sugarbeet production will be resolved in the future.

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Sugarcane

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Glossary

Bagasse Fibrous plant residue remaining after the sugar-containing juice is extracted by crushing sugarcane through milling units

Brix Percentage by weight of soluble solids in a water solution

Juice Sap expressed from the sugarcane stalk that contains dissolved sucrose formed by the plant

Massecuite Suspension of sugar crystals in their mother liquor produced during the first stages of vacuum pan crystallization

Molasses By-product remaining after crystallized sugar has been removed, by centrifugation, from the mother liquor of condensed sugarcane juice

Ratoon Sugarcane plant regrowth from germination of underground buds following harvest of the crop

Raw sugar Product of cane sugar factories, intermediate crystalline product of about 96% sucrose resulting from the removal of impurities and the evaporation of water from sugarcane stalk juice

Refined sugar Product of a sugar refinery where raw sugar is processed to remove remaining nonsugar impurities to produce a range of sugar products for human consumption

Ripening Developmental phase of the sugarcane plant at the end of the crop cycle when, owing to climate, cultural practices, flowering, or growth regulators, the crop reaches maturity, slows accumulation of fresh weight, and increases the accumulation of sucrose

Sugar Normally the disaccharide sucrose but occasionally the invert monosaccharides glucose and fructose.

Sugarcane, or sugar cane, is the common name given originally to the sucrose-storing species and now to the interspecific hybrids of the genus *Saccharum*, grown as the improved cultivars of contemporary sugarcane production. Cultivated sugarcane is a robust, vegetatively propagated perennial grass that is generally limited to latitudes within 30° of the equator or to ocean-warmed coastal areas (20°C mean air temperature isotherm) lying outside this belt (Fig. 1). The prolonged growing seasons of the tropics, coupled with the high production efficiency of sugarcane, result in extraordinarily high crop yields. Although sugar for food remains the most important product of sugarcane, by-products are a significant part of its economic production. The technologies used worldwide in sugarcane cultivation and processing range from those of low-input farming, essentially unchanged over the last millennium, to the high-input, extensively mechanized, and sophisticated technologies of modern corporate farming and factory processing. [*See* SUGARBEET.]

I. Taxonomy and Botany

A. Taxonomy

Sugarcane is a member of the genus *Saccharum*, which belongs to the family Gramineae of the order Poaceae and class Monocotyledoneae. The extensive prehistoric distribution of sweet canes by mankind, and the wide hybridization among the various forms, obfuscate taxonomic relationships among this group. At the lower hierarchic levels, the taxonomy of *Saccharum* and its relationship to intercrossing genera re-

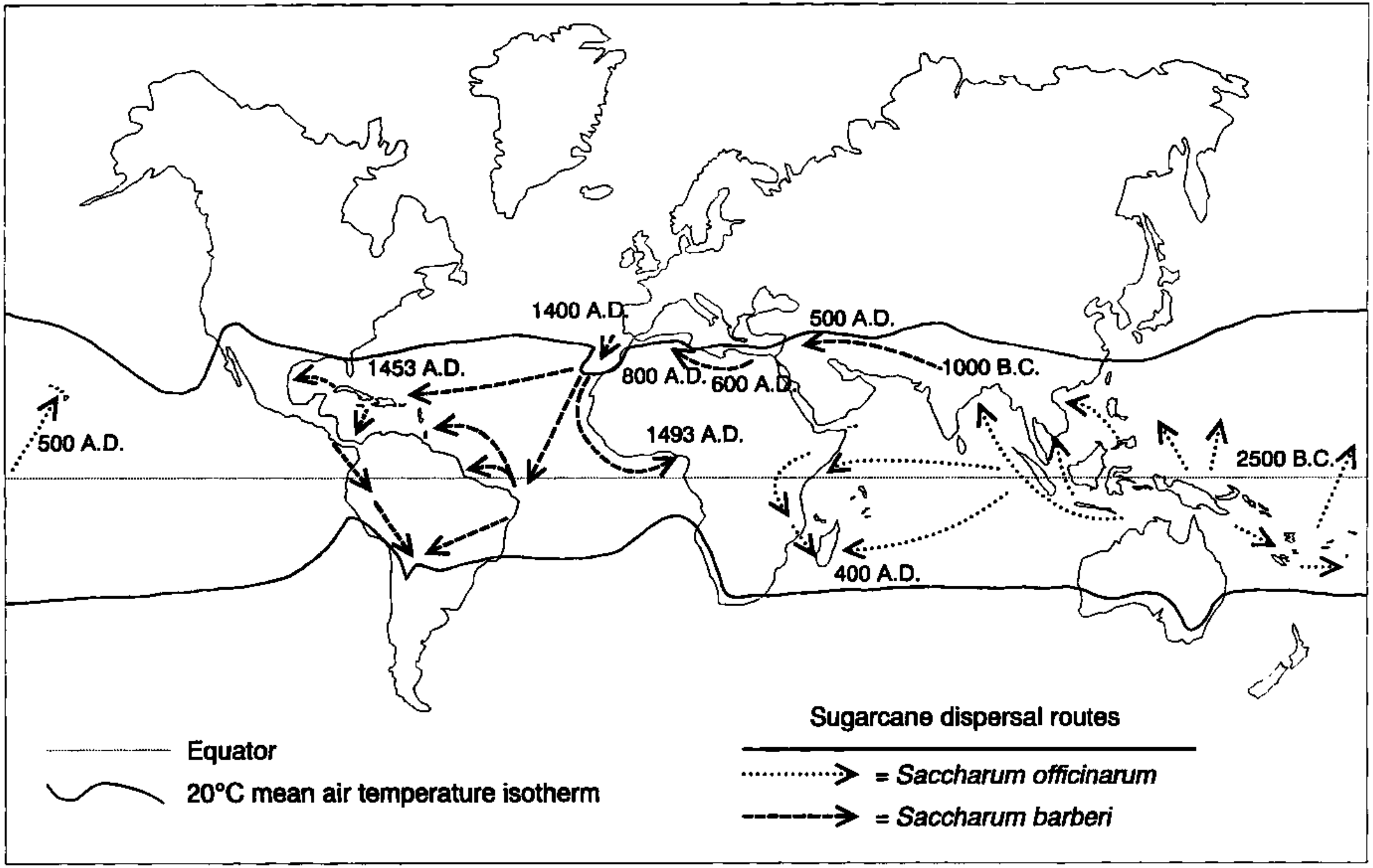

FIGURE 1 Origin, dispersal, and world distribution of sugarcane. [Modified after Daniels, J., and Roach, B. T. (1987). *In* "Sugarcane Improvement through Breeding" (D. J Heinz, ed.), p. 66. Copyright 1987 by Elsevier Science Publishers B. V., Amsterdam; and Blume, H. (1985). "Geography of Sugar Cane: Environmental, Structural and Economic Aspects of Cane Sugar Production." Verlag Dr. Albert Bartens, Berlin.]

main controversial. Characteristics of the different species of the genus are presented in Table I.

Saccharum officinarum L., type species for the genus, is the one species with continuous acceptance since Linnaeus' 1753 description. Classification of other species varies by authority. It is generally considered that sugarcane has two wild species and three or four domesticated ones. The wild species *Saccharum spontaneum* L. has a wide distribution throughout the tropics of Africa, Asia, and Oceania, whereas *Saccharum robustum* Brandes and Jeswiet ex Grassl are restricted to Melanesia and parts of Indonesia. *Saccharum sinense* Roxb., the sugarcane of China, and *Saccharum barberi* Jesw., the sugarcane of India, are considered as one species by some authorities but two by most. The domesticated *Saccharum edule* Hassk., grown as a garden vegetable for its abortive inflorescence, is restricted primarily to Melanesia and is considered to be a product of introgression of *S. officinarum* or *S. robustum* with other genera.

B. Botany

1. Plant Morphology

Sugarcane is a tall, robust, clump-forming grass (Fig. 2). Culms, usually called stalks or stems, shed their lower leaves. Aerial stalks are unbranched, stout to slender, differentiated into nodes and internodes with prominent, annular leaf scars; adventitious root primordia in a several-tiered band at each node; an intercalary meristem or growth ring above each root band; and an ovoid or deltoid axillary bud prominent in the root band. The lateral buds are inserted alternately along the stalk in the axil of leaves. Leaves are differentiated into long (1 to 2 m) blades and shorter (0.5 m), culm-clasping sheaths.

Each node is capable of giving rise to a new plant and is used for crop propagation. The shoot roots arise from underground nodes, and the axillary buds located at these nodes give rise to tillers. Depending on the clone and growing conditions, more than 100 stalks can be produced from one bud, but only 5 to 10 survive the competition in densely planted field conditions.

Sugarcane can be propagated through sexual seed. The sugarcane inflorescence is a large, open panicle with several orders of branching upon which are pairs of spikelets composed of short segments easily separated by brittle joints. Each spikelet of a pair is oblong and contains a single complete flower with long tufts of hair at its base, imparting a general silky appearance to the entire panicle (Fig. 2).

Following fertilization and development of the mature seed, the panicle disarticulates to scatter the hair-

TABLE I

Principal Characteristics of the Different Species of the Genus *Saccharum* and Number of Clones in the World Collections of Sugarcane

Species (chromosome no.)	Common name	Sucrose content (%)	Fiber content (%)	Stem diameter (cm)	Adaptability	Germplasm collection (no.)	
						United States[a]	India[b]
S. officinarum ($2n = 80$)	Noble	High 18–25	Low 5–15	Thick	Tropical and subtropical	568	762
S. sinense ($2n = 110$–120)	Chinese	Medium 12–15	High 10–15	Medium 1.4–2.2	Tropical and subtropical	38	29
S. barberi ($2n = 82$–124)	Indian	Medium 13–16	High 10–15	Medium 1.7–2.1	Tropical and subtropical	57	43
S. spontaneum ($2n = 40$–128)	Wild	Very low 1–4	Very high 25–40	Slender 0.5–0.9	Tropical and subtropical	450	724
S. robustum ($2n = 60$ and 80)	Wild	Low 3–7	Very high 20–35	Medium 1.1–1.7	Tropical wetlands	135	144
S. edule ($2n = 60$–80)	Edible	Low 3–8		Medium 1.1–1.8	Tropical		
Erianthus	Related genus	Very low	Very high		Tropical and subtropical	196	201

Note. Range values are the mean ± 1 SD of data reported on germplasm collections. Reports summarized are: 1. Sugarcane Genetic Resources. I. *Saccharum spontaneum* L. (1983). Sugarcane Breeding Institute, Coimbatore, India. 2. Sugarcane Genetic Resources. II. *Saccharum barberi*, Jeswiet; *Saccharum sinense*, Roxb. Amend Jeswiet; *Saccharum robustum*, Brandes et Jeswiet ex Grassl; *Saccharum edule*, Hassk (1985). Sugarcane Breeding Institute, Coimbatore, India.

[a] Maintained by the USDA, ARS, Miami, FL.

[b] Maintained by the Sugarcane Breeding Institute, Coimbatore, India.

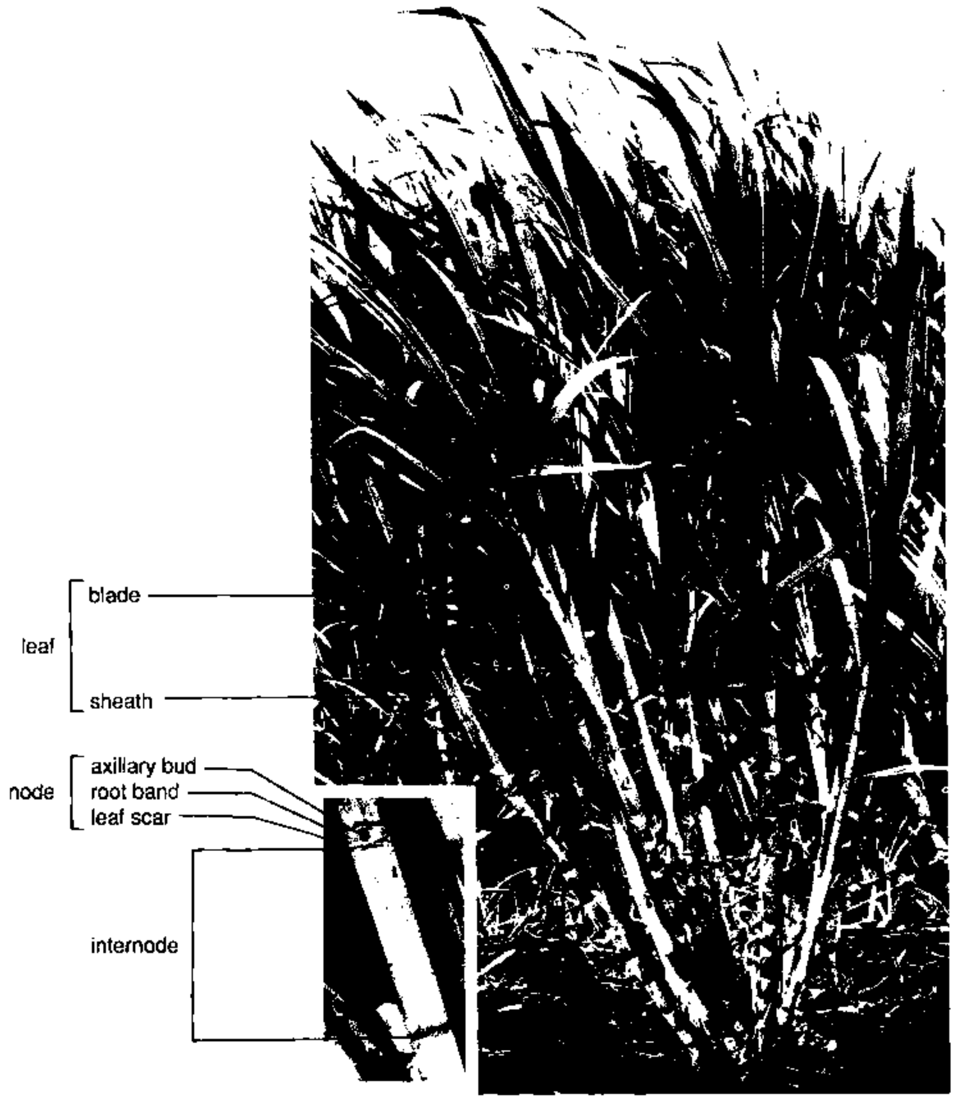

FIGURE 2 Sugarcane growth habit and details of stalk segment used as a propagule.

covered caryopses called "fuzz." Fuzz is planted in the breeding program to develop improved cultivars.

2. Physiology

Factors that maximize the amount of light absorbed by the crop are optimum leaf area per stalk and number of stalks per unit land area. These factors vary considerably with age, environment, and cultivar. The single-sided leaf blade area for commercial hybrids is approximately 0.05 m^2 per leaf; around 65 to 80 thousand stalks ha^{-1} survive to harvest and consist of one internode produced every 7 to 10 days. The laminar leaf blade of sugarcane has stomata for gas exchange on each side, and the photosynthetic mesophyll cells are arranged in the typical C-4 Kranz anatomy. Vigorous plants will carry 10 to 14 fully formed leaves for a two-sided leaf area of 1.0 m^2 per stalk, providing a leaf area index of 3 to 7.

Leaf area expansion is coupled with rate of leaf formation and stalk growth; all are closely related to air temperature. Although sugarcane shows increasing rates of photosynthesis with increasing solar radiation up to full sunlight, solar radiation is not as limiting to development as is temperature. [*See* PHOTOSYNTHESIS.]

Sugarcane was the plant which led to the discovery of C-4 photosynthesis, and it is acclaimed as a leading performer in rates of photosynthesis. Sugarcane is reported to have carbon fixation rates as high as 2.8 mg CO_2 m^{-2} sec^{-1} (63 μmol cm^{-2} sec^{-1}). Under exceptional circumstances, total dry matter produced by sugarcane may average 40 g m^{-2} day^{-1} and exceed 150 t ha^{-1} $year^{-1}$, more than half of which is partitioned into the harvested stalk which contains 30% dry matter composed of approximately equal amounts of sucrose and fiber.

II. Distribution and Improvement

A. Origin and Development as a World Crop

The origins of sugarcane are lost in folklore and mythology. Sugarcane appears in Indian mythology at about 1000 B.C., and sugar production is recorded from the Orient from 500 B.C. These facts support the hypothesis that sugarcane originated in northern India (*S. barberi*) or southern China (*S. sinense*). However, archeological records indicate that sugarcane (*S. officinarum*) originated in New Guinea as early as 2500 B.C., and myth extends this date to 6000 B. C. Cytogenetic evidence supports the hypothesis that *S. officinarum*, which is found only in cultivated settings, was domesticated from *S. robustum*. Since numerous forms of both these species are concentrated in New Guinea and adjacent islands of Melanesia, we assume that domestication of sugarcane occurred in this area. *S. officinarum* subsequently spread to Indochina and Bengal by 1000 B.C. (Fig. 1) to hybridize with *S. spontaneum* in India and China to produce the domesticated *S. barberi* and *S. sinense*.

Dispersal of *S. officinarum* into Indonesia, Malay, China, India, Micronesia, and Polynesia apparently took place during prehistoric times (Fig. 1). The spread of *S. officinarum* from Polynesia to Hawaii took place with native migrations around 500 A.D. and from Indonesia to Africa about 400 A.D. Concurrently, *S. barberi* hybrids were spread from India to the Middle East, then eastward to the Mediterranean from 600 A.D. to 1400 A.D., and finally to the New World beginning with the second voyage of Columbus in 1493. Sugarcane rapidly spread throughout Central and South America during the 1500s so that by 1600, Latin American cane sugar production was the most important in the world. Sugarcane first reached the continental United States (Louisiana) in 1750.

S. officinarum, called "noble canes," which were first observed by Europeans on their explorations in the Pacific Ocean, were higher in sucrose and lower in fiber than the Indian canes and were quickly spread throughout sugarcane growing areas. However, they were more susceptible to diseases and insects and required a program of continuous replacement of susceptible clones.

B. Breeding and Selection

The importance of cultivar development is related to the facts that sugarcane is grown as a monoculture, without crop rotation, and without fallow for tens or hundreds of years. This allows time for pests and pathogens to adapt and accumulate to crop-damaging levels. Steadily increasing yield potential makes it advantageous to replace cultivars about every 10 years.

Sugarcane underwent accelerated genetic improvement following the observation in 1858 that it produced viable seed. Until this time, it was not known that sugarcane could reproduce sexually. Following a particularly disastrous disease complex called Sereh in Java during the late 1800s, the Dutch in 1888 established an innovative breeding and selection program. The early stimulus for sugarcane breeding was to incorporate the disease resistance, hardiness, and tillering capacity of *S. spontaneum* into the sugar-producing germplasm of the noble canes. A key event in this breeding effort was the production in 1921 in Java of cvs. POJ 2725 and POJ 2878, the first of the so-called nobilized canes, which are present in the pedigrees of nearly all modern sugarcane cultivars.

Cytological studies of *S. officinarum* × *S. spontaneum* hybrids revealed a curious phenomenon which remains an enigma to the present day. The production of nobilized cultivars resulted from selection of progeny with higher chromosome numbers containing the somatic complement (NN) of the noble female parent (80 chromosomes) plus the gametic number (S) of the *S. spontaneum* male.

$$\text{NN (80)} \times \text{SS (96)} \xrightarrow{F_1} \text{NNS (80 + 48 = 128)}$$

This behavior of restitution of the female chromosomes persisted through another backcross generation to the noble but not the third. Similar chromosome behavior is seen when *S. barberi*/*S. sinense* is crossed to the nobles, as was done in India to produce the "Co" clone series, which were equally important progenitors of today's cultivars.

Today, parents are selected on the basis of their yield potential, disease and pest resistance, and progeny performance. Breeding programs have been under way long enough in most producing areas so that unique, adapted germplasm lines have been developed for the various ecological niches in each area. Crossing is conducted using paired, known combinations, or multiple combinations in a polycross. Generally, flowering stalks are excised in the field and placed in an acid solution, which allows the stalk to live long enough for cross-pollination and maturation of seed.

Selections from seedling populations take place after 8 to 10 months of growth, are asexually propagated, and go through one or more additional visual stages of selection before being placed in field yield trials. It takes 10 to 15 years from crossing to release of a new cultivar. Yield potential has increased at about 1% per year over the last 50 years.

C. Germplasm Evaluation and Preservation

Modern commercial sugarcane cultivars have germplasm from *S. officinarum*, *S. spontaneum*, *S. robustum*, and *S. barberi*/*S. sinense* but are very limited in genetic diversity. Over 60% of the world's commercial cultivars are derived from only three clones of *S. officinarum*, possibly four clones of *S. spontaneum* and *S. barberi*/*S. sinense*, and two clones of *S. robustum*. This limited sampling of clones has sparked an interest in widening the germplasm base to increase yield potential and pest resistance. Hybrids of *S. spontaneum* accessions from southeast Asia have shown promise for increasing yield potential under certain conditions in Louisiana, Hawaii, Argentina, Australia, and South Africa.

Since 1875, over 25 expeditions have collected *Saccharum* species and related genera in Indonesia (Irian Jaya, Kalimantan, Sulawesi, and Moluccas), Papua New Guinea (including New Britain), India, China, Thailand, The Philippines, and Taiwan. Sampling techniques on these expeditions emphasized broad sampling of clonal types to ensure the collecting of diverse genetic material.

The genera and species of *Saccharum*, related genera, and numbers of clones in the world collections of sugarcane are listed in Table I. To the degree possible, the two locations are duplicate clonal repositories. Seed from 160 clones of *S. officinarum*, stored in liquid nitrogen for long-term preservation, are in the U.S. National Seed Repository at Fort Collins, Colorado.

Geographical areas with endangered germplasm needing further collection are in Pakistan, Burma, and Irian Jaya. Classification and characterization of the collections are now under way to develop core collections of each of the groups, to determine genetic diversity and the best methods for preserving and maintaining the germplasm.

III. Yields and Crop Cycles

A. Regional Productivity and Yields

The 1990 cane sugar production of 98.2 million metric tons (Mmt) of sugar included 69.8 Mmt centrifugal raw sugar, 12.8 Mmt noncentrifugal raw sugar, and the equivalent of 15.6 Mmt sugar that was fermented into ethanol (Table II). Countries with the largest area under cane cultivation are Brazil, India, China, and Cuba; collectively these four countries account for 59% of the area under cultivation and 67% of the cane sugar production worldwide.

The world average of 61 t cane ha^{-1} and 5.82 t sugar ha^{-1} represent fresh weight yields and product yields well above those for other crops. The highest fresh weight crop yields are generally ascribed to tuber crops, e.g., potatoes average 15.1 t ha^{-1}; but this is only 25% of world average cane production. The highest product yields are generally ascribed to the cereal grains, e.g., 3.70 t ha^{-1} maize grain, which is 64% of the processed sugar yield of cane. Therefore, although the total productivity of sugarcane ranks only about eighth among crops, this is primarily due to the processed character of its product, sucrose, and its smaller area under cultivation; on a dry weight basis, sugarcane yields are the highest among crops.

Factors that contribute to high yields of sugarcane are its perennial growth habit and continuous accumulation of sucrose in the vegetative plant structure. Crop cycles vary from less than 10 months in temperate areas such as Pakistan and Louisiana, where killing frosts set rigid seasons, to 24 months in Peru and South Africa, and sometimes longer in Hawaii (Table II). Most of the sugarcane in other parts of the world is grown in 14- to 18-month plant crops and 12-month ratoons. Crop cycles average just over 15 months for the highest-producing countries. Sugar yields are also affected by the length of the harvest and milling season. In most countries, milling is limited to the 5 or 6 months in the coolest part of the year that produces the ripest cane. At the other extreme are Hawaii with a 10- to 12-month harvest season and Louisiana with a 3-month harvest season.

B. Production Efficiency of Sugar Yield

The yields of cane sugar per hectare can be used for comparing the efficiency of production among differ-

TABLE II

Sugarcane Production and Yield Statistics for Countries Producing More Than 500,000 Tons Centrifugal Raw Sugar in 1990

Region Country	Area harvested (1000 ha)	Cane production (1000 t)	Cane yield (t ha^{-1})	Sugar, CR[a] production (1000 t)	Sugar, N[b] production (1000 t)	Sugar E[c] production (1000 t)	Sugar yield[d] (t ha^{-1})	Growth period (months)	Harvest and milling season	No. of ratoons
Africa	1202	72,982	60.7	7,572[e]	89		6.37			
Egypt	118	11,143	94.7	975			8.26		May–Jun	
Mauritius	76	5,548	72.8	624			8.21	12–18	Jun–Dec	8–9
S. Africa	272	18,700	68.8	2,230			8.20	12–24	May–Jan	3–7
Swaziland	40	3,800	95.0	500			12.50	12–18	May–Dec	7–8
Asia	7229	426,006	58.9	29,578[e]	11,130		5.63			
China, PR	1068	63,970	59.9	4,937[e]	430		5.02	10–16	Nov–Apr	1
India	3430	220,000	64.1	11,946	8,200		5.87	9–18	Sep–Mar	1–2
Indonesia	369	25,503	69.1	2,180	45		6.03	12–16	May–Oct	0–1
Pakistan	854	35,493	41.6	1,993[e]	1,150		3.68		Oct–Jul	
Philippines	315	24,800	78.7	1,740	21		5.59	12	Sep–Apr	1
Thailand	686	33,561	48.9	3,641	615		6.20	10–14	Nov–Jun	2–3
N & C America	2701	173,278	64.1	17,016[e]	246		6.39			
Cuba	1350	77,000	57.0	8,050			5.96	12–20	Oct–Jun	4
Dominican Republic	170	7,000	41.2	620	38		3.87	11–18	Nov–Jun	4–6
Guatemala	109	7,400	67.8	726	58		7.19		Nov–Jun	
Mexico	350	34,893	99.7	3,406			9.73		Nov–May	2–3
USA (FL, LA, TX)[f]	265	17,246	65.1	1,981			7.47		Oct–May	1–4
United States (Hawaii)[g]	29	5,938	203.8	744			25.54	20–36	Jan–Dec	0–2
S. America	5327	332,016	62.3	12,972[e]	1,303	15,630	5.61			
Argentina	330	16,000	48.5	1,367			4.14	10–16	Jun–Nov	6–7
Brazil[h]	4269	263,604	61.7	7,900	240	15,630	5.57	12–16	Jun–Oct	5
Colombia	304	24,466	80.6	1,695	978		8.79	16–18	Jan–Dec	5
Peru	62	6,965	112.3	603	21		10.06	16–24	Jan–Dec	4–8
Venezuela	100	7,000	70.0	557	10		5.67		Sep–Aug	
Oceania	414	30,559	73.8	4,094			9.89			
Australia	340	26,226	77.1	3,570			10.50	12–16	Jun–Dec	2–5
World total[i]	16,878	1,035,096	61.3	69,752[i]	12,768	15,630	5.82			

Source. "FAO Yearbook Production," Vol. 44 (1990). Food and Agriculture Organization of the United Nations.

[a] CR, centrifugal raw sugar.

[b] N, noncentrifugal raw sugar.

[c] E, equivalent amount of raw sugar fermented to ethanol.

[d] Tons sugar per hectare based on total production of centrifugal plus noncentrifugal raw sugar plus fermented equivalent raw sugar.

[e] Regions and countries producing both cane and beet sugar; the FAO statistics were reduced by fraction of cane sugar to total sugar from data in "FO Lichts World Sugar Statistics 1990/91."

[f] FL, Florida; LA, Louisiana; TX, Texas. Data from "Agriculture Statistics 1991." United States Department of Agriculture. U.S. Government Printing Office, Washington, DC.

[g] Data from "Hawaiian Sugar Manual 1991." Hawaiian Sugar Planters' Association, Aiea, HI.

[h] FAO data on Brazil fail to credit 68% of the sugar production that is diverted to ethanol fermentation. Ethanol data for Brazil from personal communication with G.R. Machado, Centro de Technologia Copersucar, Piracicaba, SP, Brazil.

[i] The total for the world is greater than that for the continents listed, and totals for continents are greater than the sum of the countries listed.

ent countries and regions and for evaluating factors contributing to these efficiencies. The top-ranking countries or regions in total efficiency of production are Hawaii, Swaziland, Australia, Peru, and Mexico (Table II). Total efficiency of cane sugar production depends upon the biomass produced, which is expressed in terms of the yield of sugarcane per hectare and the sugar recovery, i.e., the amount of sugar produced as a percentage of the crushed cane. Sugar recovery depends on the sugar mill recovery efficiency and the quality (i.e., sugar vs nonsucrose impurity content) of the cane.

Biomass is the factor that contributes most to production efficiency. The importance of biomass is revealed in this data set by comparing the coefficient of determination between biomass and sugar yield ($r^2 = 0.87$) vs sugar recovery, defined as tons sugar per ton of cane, and sugar yield ($r^2 = 0.33$). Consequently, greatest productivity gains have been made through efforts to increase biomass. [*See* BIOMASS.]

IV. Cultural Practices

Sugarcane is grown over a wide range of climatic, economic, and social environments. This results in diverse cultural practices, ranging from unmechanized, low material inputs and low yields of undeveloped regions to highly mechanized crop cultivation with high inputs of fertilizers, insecticides, as well as irrigation and growth regulators to achieve high yields. This latter cropping system is covered in the following discussion.

A. Planting and Ratooning

Preparation varies according to soil conditions and the mechanized capabilities of the farm. Soils include the major tropical and subtropical orders with extreme differences in organic matter and physical characteristics.

The sugarcane crop is planted by machine or by hand with vegetative stem cuttings called "seed," seedpieces, or setts sometimes treated with heat and a fungicide. The propagation material is cut from seed fields or, more typically, from designated areas of commercial fields. In areas subject to freezing or drought during germination and early growth, long seed consisting of whole stalks with 10 to 15 buds may be used. Under less severe conditions, seedcane is cut into smaller sections of 0.3 to 0.6 m, which includes 3 or 4 buds.

Sugarcane is planted at row widths varying from 0.9 m in areas having short cropping seasons to 1.8 m, depending on mechanization and length of crop cycle. An exception to this occurs when sugarcane is planted in alternating wide (1.8 m) and narrow (0.9 m) interrows to accommodate a single drip irrigation tube between the narrow interrows.

Depth of planting is a compromise between shallowness needed for a high percentage of emergence from the soil and depth needed for avoiding freeze killing and dehydration and for ensuring adequate buds for good tillering.

Sugarcane can be germinated in a nursery and then transplanted to the field, but this technique is generally too costly to be widely used for normal field operations. It may be used for rapid spreading of new cultivars or as a way of certifying that the clone is free of diseases.

Multiple ratoon crops of sugarcane may be harvested from a single planting by regrowth from stubble. Ratoons originate from germination of axillary buds on the short underground internodes remaining after the above-ground stalk is harvested. The number of ratoons possible from a single planting is the result of an interaction of the multiple factors of cultivar, soil type, depth of planting, disease incidence, weed infestation, and how badly the stool was damaged by harvest. It is common to grow 2 or 3 ratoons; under ideal conditions the number can exceed 10.

Most sugarcane crops are "fired" or "burned" either as a standing crop prior to harvest or occasionally after harvest to remove the accumulated dead leaf trash. However, the crop may be harvested unburned, in which case the residual leaf trash may reduce soil water loss, soil erosion, and weed growth and improve establishment of the ratoon crop.

B. Fertilization

Nutrients are supplied from the residue of the previous crop, in irrigation water, and from applied fertilizer. Sugarcane is an efficient user of nitrogen (N) based on dry matter yield. Management of the timing and placement of N is critical for the production of high yields of sugar; high levels of N are required for the rapid early growth of the crop, but plant N levels must be low near time of harvest to promote maximum sucrose storage. Leaf blade N is used as an index of nitrogen status of the crop to optimize fertilizer applications, especially in long-cycle crops. [*See* FERTILIZER MANAGEMENT AND TECHNOLOGY.]

The requirements of potassium (K) and phosphorus (P) are highly variable; soil analysis is used to determine required applications. The requirement for P is high on upland soils owing to the adsorption or fixation of P under acidic conditions. As a result, fertilizer P is usually applied in amounts greatly in excess of the actual crop requirement. [*See* SOIL FERTILITY; SOIL TESTING.]

Sugarcane grown on acidic upland soils may benefit from liming (application of calcium carbonate) to improve the availability of P and to reduce the availability of toxic concentrations of aluminum and manganese. Calcium silicate is used as an amendment in muck soils of Florida and in amorphous sesquioxide soils of Hawaii and South Africa.

Critical tissue levels and deficiency symptoms for most elements are well documented; nevertheless, nutrients other than N, P, K, and Ca are rarely used on a wide scale. Spot applications of minor elements are occasionally made to correct local mineral nutrient deficiencies.

C. Water Requirement and Application

The high quantity of biomass produced requires a large amount of water. In Hawaii, areas with less than 200 cm of rain annually receive irrigation. About 60% of Hawaii's cane land is irrigated, and 90% of this is through drip systems. Other methods of irrigation include adjustment of the water table and water application by flooding, furrow irrigation, or sprinklers. The method used depends on availability of water, labor, operational energy, land slope, technical skill of the farmer, yield return, and material availability and costs. [*See* IRRIGATION ENGINEERING, FARM PRACTICES, METHODS, AND SYSTEMS.]

The most technically difficult, but labor- and water-conserving system, is drip irrigation, which utilizes plastic tubes to uniformly distribute water along the crop row. Because of the low pressure and small distribution orifices, water entering the drip irrigation system must be free of suspended solids, which are removed by screening and filtration. Chlorination reduces biological growth in the tubing; otherwise the growth would plug orifices and disrupt water distribution. Drip irrigation in Hawaii has improved water distribution efficiency, increased yields, and reduced labor costs compared to the earlier furrow and sprinkler systems.

Under controlled conditions, sugarcane exhibits a linear relationship between total dry matter production and water consumption (7 to 9 g liter^{-1}). A large proportion of the world production of sugarcane is not irrigated and is subjected to alternating wet/tropical and dry/subtropical seasons. If there are no prolonged periods of drought during the wet growing season, the crop yield potential is roughly 1 t cane stalks cm^{-1} evapotranspiration. Therefore, it is possible to use evaporation data and water budget analysis to estimate yields and to characterize factors limiting this potential.

D. Pests

1. Diseases

Sugarcane is susceptible to at least 8 bacterial, 152 fungal, and 7 viral diseases; the major diseases worldwide are smut, rust, red rot, leaf scald, ratoon stunt disease, and viral diseases (Table III). Most growing areas impose quarantine to prevent the distribution of disease pathogens, but diseases are fairly widely distributed around the world, requiring the planting of resistant cultivars to control them. [*See* PLANT PATHOLOGY.]

TABLE III

Major Sugarcane Diseases of the World: Causal Organism, Common Name, and Type of Infection

Causal organism	Common name	Symptom[a]
Bacterial diseases		
Clavibacter xyli subsp. *xyli*	Ratoon stunt	S
Pseudomonas rubrilineans	Red Stripe	L,S
Xanthomonas albilineans	Leaf scald	L,S
Xanthomonas campestris pv. *vasculorum*	Gumming	L,S
Fungal diseases		
Bipolaris sacchari	Eye spot	L
Ceratocystis paradoxa	Pineapple	sett
Cochliobolus stenospilus	Brown stripe	L
Fusarium moniliforme	Pokkah boeng	T
Glomerella tucumanensis	Red rot	L,S
Mycovellosiella koepkei	Yellow spot	L
Peronosclerospora sacchari	Downy mildew	L
Puccinia melanocephala	Rust	L
Stagonospora sacchari	Leaf scorch	L
Ustilago scitaminea	Smut	S
Viral, viruslike, or mycoplasma diseases		
	Chlorotic streak	L
	Fiji disease	L,S
	Grassy shoot/	L,S
	white leaf	L
	Streak	L
	Sugar cane mosaic	

[a] L, leaf; T, top leaf spindle and apex; S, systemic and stalk; sett, seed piece.

Phytosanitary measures such as heat therapy can temporarily control some of the diseases. The seedpiece rotting diseases can be controlled with appropriate fungicides, otherwise no fungicides are used for control of sugarcane diseases. [*See* FUNGICIDES.]

2. Weeds

Although sugarcane is a robust grass, it competes poorly with weeds owing to its relatively slow early growth rate and wide interrow spacing. After the canopy closes, the crop can compete with most weeds. Perennial grasses and vines are the most serious weed problems. Nevertheless, many annual broadleaf and grass species also infest the crop and reduce yields. Particular weed species tend to be regionally important problems. [*See* WEED SCIENCE.]

Weed control techniques include mechanical cultivation and application of pre- and postemergence herbicides. Integrated methods of control are used with reliance on cultivation and the use of herbicides just after planting until canopy closure. Nonchemical methods of control such as trash blanket culture resulting from harvest of unburned cane are being used in some regions. [*See* HERBICIDES AND HERBICIDE RESISTANCE.]

3. Insects

Insects of the orders Homoptera, Lepidoptera, Coleoptera, and Hymenoptera can be serious pests of the sugarcane plant; termites of the family Isoptera sometimes destroy setts, preventing germination; army worms, cutworms, and stalk borers may be damaging to young crops. Among the most destructive insect pests to older plants are the larvae of the stalk-boring moths and beetles, the root grubs of beetles, and other locally important insects. Other insects such leafhoppers cause little direct damage and serve as vectors for the spread of diseases, especially viral diseases such as Fiji disease.

Control of insects is based on integration of cultural practices and use of host genetic resistance, biological agents, and a small amount of chemicals. Most success has been experienced with host resistance and the introduction of biological control insects. In some areas of the world insecticides are used on particular sugarcane insect pests, but none are currently used in Hawaii. [*See* INTEGRATED PEST MANAGEMENT; PEST MANAGEMENT: BIOLOGICAL CONTROL; PEST MANAGEMENT: CHEMICAL CONTROL; PEST MANAGEMENT: CULTURAL CONTROL.]

4. Nematodes

Nematodes are potentially a serious threat to sugarcane, especially to crops grown on sandy soils. There is considerable genetic resistance to nematodes so that control can be achieved through an active breeding and selection program for these pests. However, nematicides are used in some areas. [*See* NEMATACIDES.]

5. Rodents

Rats gnaw cane and may be very damaging primarily by attracting boring insects and facilitating the entry of pathogenic microbes. In general, rodents prefer soft, low-fiber cultivars of high sugar content. Gnawed stalks soon ferment and deplete sugar owing to infection by various organisms, the major cause of losses. Control is by genetic resistance and poison baits. Susceptible cultivars without control may experience up to 80% of the stalks damaged by rats, and damaged stalks may cause a 50% reduction in yield.

E. Flower Prevention

Flowering, called tasseling or arrowing, can be quite detrimental to yields, especially when the crop cycle extends months beyond time of flowering. Since flowers are monopodal, stalks cease production of new leaves and internodes after flowering, apical dominance is broken, allowing the germination of axillary buds, the stalks may become pithy, reducing sugar content and thus resulting in lower yields.

Sugarcane flowering is initiated when the day lengths in autumn shorten to about 12.5 h; panicle emergence occurs 3 months later. Since induction of flowering occurs only once annually during a 3-week period, treatments can be applied shortly before this period to prevent it. Flowering can be prevented by moisture stress, by light interruption of the night, and most practically and successfully by chemical inhibition with herbicides or growth regulators, especially with application of the growth regulator ethephon 15 to 30 days prior to the induction period. In Hawaii, such treatments are used on heavily flowering cultivars grown in heavily flowering environments, resulting in yield increases of around 0.5 t sugar ha^{-1}.

F. Ripening

Cultivars differ during crop development in the fraction of dry weight growth partitioned into fiber to support increase in size and into stored sucrose. Generally, throughout the crop cycle, the tissue moisture percentage drops steadily from about 85% in very young cane to 70% in mature cane. Meanwhile sucrose rises steadily from less than 10% to more than 45% of the dry weight. This trend of development results in juice with a Brix of 20 or more, of which more than 90% is sucrose. This natural trend of maturation is referred to by sugarcane growers as ripening. Ripening can be stimulated by decreased water availability, cool temperature, low levels of nitrogen, and growth-regulating chemicals. In many sugarcane growing areas, significant levels of natural ripening occur during the cool, dry winter season. However, in areas like Hawaii, the dry season coincides with rapid growth during summer and the wet season is the time of cool, growth-limiting temperatures. Therefore, in Hawaii, seasonal ripening is not sufficient for optimal production. In addition, optimal economics of employing labor and operating mills and other specialized equipment necessitate harvesting throughout most of the year. Consequently, alternatives to natural ripening are employed. In Hawaii, a combination of limiting nitrogen application to the early part of the crop cycle, withholding water at the end of the crop cycle, and application of growth-regulating chemicals are used to ripen the sugarcane crop. Compounds with potential to enhance ripening are glyphosate, ethephon, and fluazifop. Glyphosate is the only ripener used commercially in Hawaii.

G. Harvesting

Most of the world's sugarcane crop is harvested by hand. Where labor is unavailable or too costly, machines are used. Because of the high biomass yields and varied terrains under cultivation, sugarcane harvesting equipment is always heavy-duty. Custom manufactured sugarcane harvesters are suitable for annual crops having relatively low yields. These specialized harvesting machines are usually equipped with ground level knives and a topping mechanism to harvest the crop while removing the immature top with its attached leaves. Such equipment is generally not suitable for high-yielding biennial crops such as that grown in Hawaii.

Mechanization of harvesting operations has increased the losses from wet weather harvesting by increasing the quantity of extraneous material which must be handled both in transport and in the mill. These losses usually balance the lower overhead costs when equipment and operation costs are spread over a long harvesting season.

V. Processing and Utilization

A. Milling and Raw Sugar Production

The production of centrifugal cane sugar and products from juice fermentation is capital-intensive as it involves complex factory processing (Fig. 3). The cane crop delivered from the field is normally weighed as it enters the factory where it is cleaned and then prepared by shredding and crushing. The prepared cane passes through a milling tandem where water is added to facilitate extraction of juice, leaving the fibrous residue, or bagasse, as the first by-product. The extracted juice typically contains about 12% solids, of which about 87% is sucrose. An alternative to milling is the diffusion process in which the cane is finely shredded and placed in a tank where the sugars are washed out from the ruptured juice storage cells. Bagasse after dewatering is carried by conveyors to the boiler furnaces or to storage.

The juice from the extraction unit is clarified by lime or other agents (e.g., magnesium oxide) and heat to precipitate soil and organic matter. The clear juice is evaporated to thick syrup from which the sugar is crystallized. Finally, the massecuite (mixture of sugar and impurities) is separated in the centrifugals into raw sugar and the by-product molasses.

In the developing countries of Africa, Asia, and South America, a noncrystalline sugar called jaggery, gur, panella, or khandsari is produced without the extensive and expensive separation of crystalline sucrose for centrifugal sugar production. These noncentrifugal sugars are for local market consumption instead of world trade. In processing noncentrifugal sugars, the expressed juice may or may not be clarified prior to being concentrated. After concentration the syrup is put into earthenware pots or molds in which the syrup solidifies. Countries with high production of noncentrifugal sugar include India, Pakistan, Colombia, and Thailand (Table II).

One ton (1000 kg) of processed sugarcane in Hawaii provides approximately 125 kg sugar, 160 kg bone dry bagasse, and 34 kg molasses. Because of its calorific value, bagasse has been traditionally used as fuel in the boiler furnaces of the sugar mills. One ton of bone dry bagasse fiber has the energy equivalent of 2 bbl fuel oil.

B. Refining

Raw sugar, which is 96 to 99% sucrose, also contains high- and low-molecular-weight colorants that are removed during the refining process. Refining involves dissolving raw sugar and treatment with adsorbents such as bone char or granular carbon to remove the colorants. This is followed by recrystallization and centrifugation to form refined white sugar and refiners molasses. For the production of liquid refined sugar used in beverages and canning,

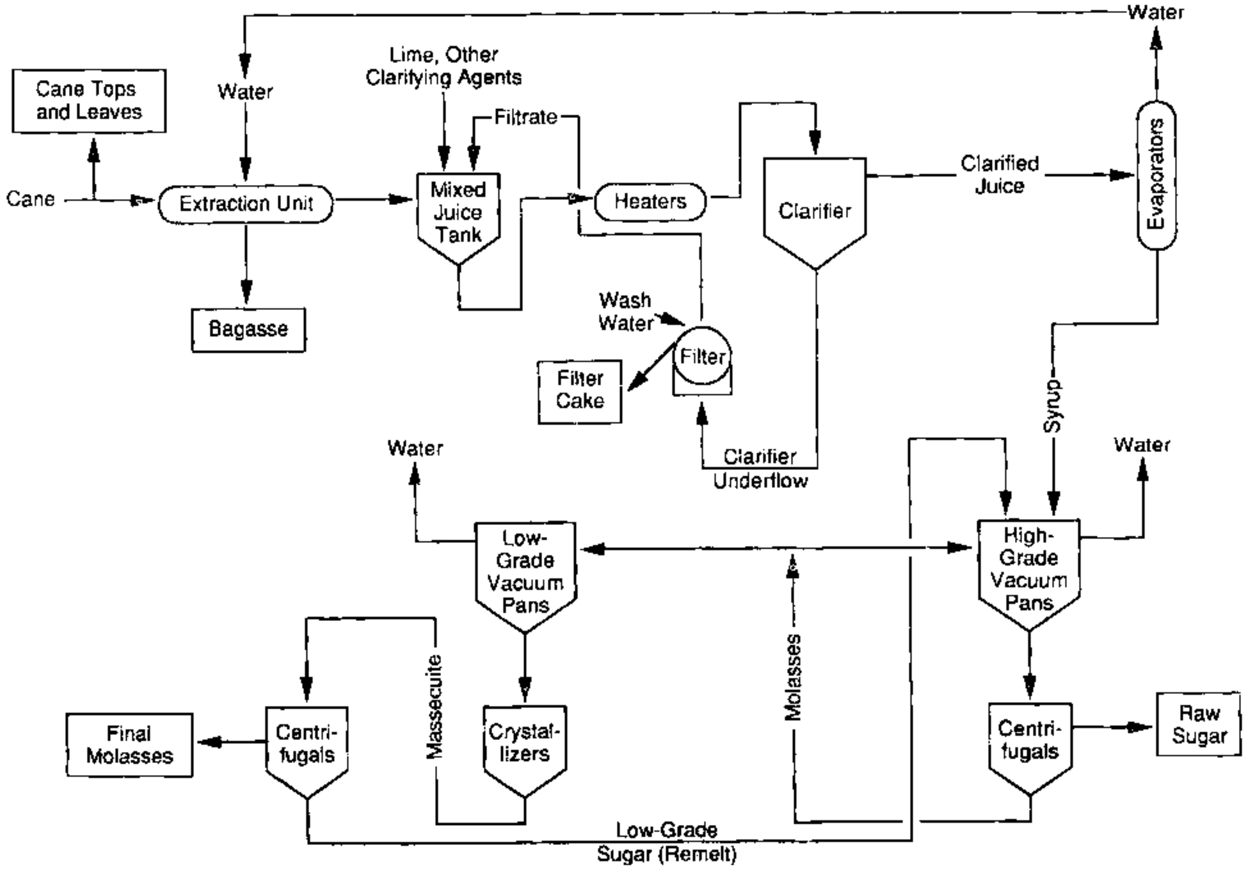

FIGURE 3 Simplified flow diagram of centrifugal cane sugar factory processes and prime products.

the recrystallization step is omitted. Brown sugar is produced by crystallization in massecuites containing molasses and by addition of such molasses to the refined sugar.

C. By-products

The by-product uses to which sucrose bagasse and molasses have been applied are varied and numerous (Table IV). Bagasse is composed of cellulose, hemicellulose (pentosans), and lignin. Fiber products, primarily paper, can be obtained from the cellulose while furfural and its derivatives are obtained from the pentosans, and plastics are potentially derived from the lignin. Molasses solids consist of 60% combined sucrose and invert sugars and about 13% inorganic salts, with the remainder being organic nonsugars. Because molasses is rich in sugars it is used primarily as a feed supplement, chemical raw material, and a nutrient for microorganisms producing a number of organic compounds such as ethanol, butanol, acetic acid, citric acid, and glutamic acid. The principal product of sugarcane, sucrose, is primarily a food, but research has shown that this also can be used as a raw material for production of higher value products (Table IV).

VI. Contemporary Issues

A. Sugarcane Burning

Prior to harvest, the sugarcane crop is burned in most high production areas to reduce the amount of biomass trash transported to the mill. Burning generally improves sugar recovery. However, if burned cane is left in the field for extended periods, substantial degradation may occur. Loss of sucrose is especially rapid when the air temperature is high. Environmental objections to field burning are related to the release of particulate plant material, CO_2, and other gases. Although cane is routinely harvested unburned in some regions, notably Queensland, Australia, harvesting is still more efficient following burning. Sugarcane trash resulting from green harvest may be

TABLE IV

Actual and Potential By-products of the Cane Sugar Industry

Bagasse, cane tops, and leaves	Sucrose	Molasses
Power generation	Foods and beverages	Animal feed
Charcoal		Potassium fertilizer
	Invert syrup	
Gasification products	Fructose	Ethanol
Pulp and paper	Fatty acid esters	Amino acids
Fiberboard	Poly(hydroxybutyric) acid	Vitamins
Particleboard	Polyether polyols	Antibiotics
Animal litter	Chlorosucrose sweetener	CO_2
Mulch	Sucrose octaacetate	Citric acid
Furfural	Sucrose octabenzoate	Yeast
Cellulose/glucose	Sucrose acetate/isobutyrate	Acetone/butanol
Xylan/xylose/xylitol	Ethanol	
Lignin	Dextran gum	
Ethanol	Xanthan gum	
Single-cell protein	Gluconic acid	
	Itaconic acid	

burned after harvest to aid in cultivation for planting the next crop.

Methods to separate leafy biomass from millable cane at the factory might allow improved recovery of sucrose and thus negate the advantage of burning. A higher value for cogenerated electricity would encourage growers to recover leafy trash rather than burn it in the field.

B. Soil Conservation and Groundwater Protection

Sugarcane is an excellent soil conservation crop, especially where multiple ratoons are grown and where the cropping cycle is long.

Recent legislation in the United States requires growers of annual crops and certain commodity crops, including sugarcane, to reduce soil erosion on land classified as highly erodible. Approved cropping practices vary according to the soil erosion risk.

Groundwater stewardship is another environmental issue of concern. Crop protection chemicals, primarily herbicides, are being detected in groundwater at the parts per billion level. Steps under way to reduce the level of contamination include rotation of herbicides, use of lower rates with more effective timing, and replacing broadcast application with band application.

Surface run-off water containing nutrients and pesticides will require development of yield response curves, more efficient application methods, and soil conservation methods to minimize the potential for environment contamination.

C. Biomass and Cogeneration

Excess bagasse can be used to generate electricity for sale to public utilities. In Hawaii, 1.0 t processed cane results in the sale of 70 kWhr of electricity in excess of that required for the mill and plantation use. The proportion of electricity supplied by the plantations for public use can be significant, especially in the less populated areas. Cogenerated electricity from sugarcane currently supplies about 20% of the total energy on three of the four sugar-producing islands of the state of Hawaii. One cogeneration factory is in place in Florida; others are obtaining permits. Cogeneration from sugarcane in Mauritius reportedly supplies 20 to 30% of that island nation's electrical power. In addition, some countries, e.g., The Philippines, are showing increased interest in recovering crop leaves and tops for use as cogeneration fuel.

D. Fermentation Products

The fact that sugarcane juice could develop intoxicating qualities was known in ancient times; however, the preparation of sugarcane rum as a by-product from molasses began during the 17th century with the development of the sugar industry in the Caribbean. In addition to potable alcoholic products, various grades of ethyl alcohol from molasses are produced in several countries.

The greatest experience with sugarcane fermentation has been in Brazil where about two-thirds of the sugarcane crop is directly used for ethanol production. Brazil began ethanol production in 1975 as a direct consequence of the 1973 world oil crisis. The ethanol industry was developed to lessen Brazil's dependence on imported oil since it had a high capacity for sugarcane production (Table II). Since the beginning there has been a dramatic increase in production, reaching 1.3×10^6 m^3 anhydrous alcohol and 10.5×10^6 m^3 hydrated alcohol during the 1990 milling season. The total 11.9×10^6 m^3 ethanol is roughly equivalent to 200,000 bbl per day of petroleum. Part of this ethanol has been used as a solvent and for the production of important derivatives for chemical industries (Table IV). However, the primary use is for automotive fuel; in 1988, approximately 3.6 to 4.0 million vehicles were running purely on hydrated ethanol (30 to 33% of the total Brazilian fleet). Low prices of petroleum and an excess of gasoline has forced the Brazilian government to withhold subsidies for the ethanol industries, reducing the number of ethanol-driven cars. Future production capacity will be determined by the relationship between gasoline and sugar prices. The Brazilian experience has shown how to implement a large bioenergy program and the critical role played by government support programs.

E. Increased Value Products

The general conversion of sucrose by chemical processes into products of greater worth is generally termed sucrochemistry. These products are derived through fermentation, synthesis, or degradation (Table IV).

F. Biotechnology

Sugarcane improvement through traditional breeding methods has had a phenomenal success, but current rates of yield increases are slow. The tools of biotechnology, including cell and tissue culture, genetic engineering, molecular biology, and genomic analysis, have the potential for accelerating genetic gains.

Considerable success has been met in learning how to manipulate foreign genes for the improvement of sugarcane through genetic transformation. Most phases of tissue culture have been developed for sugarcane. This has allowed transient transformation of sugarcane protoplasts through electroporation and stable transformation of embryogenic tissue cultures into plants transformed with selectable marker genes. Native sugarcane genes are being cloned and used to transform sugarcane to confirm the suspected function of these genes.

Identifying and characterizing the genes for manipulation are being done with molecular markers (RFLPs, restriction fragment length polymorphisms; and RAPDs, random amplified polymorphic DNA). Molecular markers have produced the first genomic maps of sugarcane. Genome maps will be used to direct breeding efforts in a more efficient manner, assess genetic diversity, and detect major genes, as well as to develop phylogenetic and evolutionary relationships among the *Saccharum* species. Ultimately, a saturated genome map will allow the use of markers, based on their map position, to clone agronomically important genes for subsequent use in transformation.

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Sustainable Agriculture

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Glossary

Agroecology Agroecological approach to the study and management of agricultural systems

Agroecosystem Agricultural system which encompasses interacting biological, technical, and socioeconomic factors, some of which are under human control, for the purpose of producing food and fiber

Agroforestry Food production system which includes multipurpose trees as part of the ecosystem

Biodiversity Collection of animal, plant, and microbial species which provide key ecological services to local agroecosystems

Ecosystem System made up of a community of plants, animals, and other organisms and their interrelated physical and chemical environment

Intercropping Planting of two or more crops together in various configurations of time and space

Monoculture Highly simplified cropping system which involves the planting of only one crop in a season

Shelterbelts Barrier zone of trees, plants, or shrubs planted to protect crops, soil, etc. from strong winds or to provide habitat for beneficial insects and wildlife

Sustainable agriculture refers to a mode of farming that attempts to provide long-term sustained yields through the use of ecologically sound management technologies such as crop diversification, organic soil management, and biological pest control. The principles of agricultural sustainability are provided by agroecology, a scientific methodology which regards agricultural systems as ecosystems (hence, the term agroecosystem) and, as such, farming and research are not concerned with high yields of a particular commodity, but rather with the optimization of the system as a whole. It also requires us to look beyond production economics to consider broader issues of ecological stability, sustainability, social equity, and cultural acceptability. For this reason, a wider definition of agriculture as sustainable means that it is

- ecologically sound: the quality of natural resources is maintained and/or enhanced;
- economically viable: farmers can produce enough for self-sufficiency and obtain adequate income by emphasizing efficient use of locally available resources;
- socially just: resources and power are distributed in such a way that the basic needs of all members of society are met, and their rights to land use, adequate capital, market opportunities, and technical assistance are assured;
- humane: all forms of life (plant, animal, human) are respected.
- adaptable: rural communities are capable of adjusting to the constantly changing farming conditions.

I. Introduction

In agricultural development, raising production is often given primary attention, but there is an upper limit to the productivity of agroecosystems. When this is exceeded, agroecosystems may degrade and collapse. For this reason in sustainable agriculture the performance criteria to evaluate agroecosystems must, in addition to productivity, be broadened to include properties of sustainability, equity, and stability.

1. Sustainability relates to the ability of an agroecosystem to main production through time, in the face of long-term ecological constraints and socioeconomic pressures. It also relates to the resiliency of an agroecosystem, i.e., its ability to recover after being subjected to stress. Productivity in agricultural systems cannot be increased indefinitely. A ceiling is placed on potential productivity by the physiological limits of crops, the "carrying capacity" of the habitat, and the external costs incurred during efforts to increase production. This point is the "management equilibrium" where the agroecosystem, considered to be in equilibrium with environmental and management factors, produces a sustained yield. The characteristics of this balanced management will vary with different crops, geographical areas, and energy inputs and, therefore, will be highly "site specific."

2. Equity is a measure of how evenly the products of the agroecosystem (income, produce, etc.) are distributed among the local producers and consumers. However, equity is much more than simply a matter of an adequate income, good nutrition, or a satisfactory amount of leisure. Many aspects of equity are not easily definable or measurable in scientific terms. To some, equity is reached when the distribution of opportunities or incomes within producing communities really improves. Clearly, although "improvements" may be a step toward equity, they do not guarantee the establishment of a more "equitable" society. Generally, this is dependent on the political structure of each country.

3. Stability is the constancy of production under a given set of environmental, economic, and management conditions. Some ecological pressures are rigid constraints in the sense that the farmer is virtually unable to modify them. In other cases, the farmer can improve the biological stability of the system by choosing more suitable crops or developing methods of cultivation that improve yields. The land can be irrigated, mulched, manured or rotated, or crops can be grown in mixtures to improve the resilience of the system. The farmer can supplement family labor through the use of either animals or machines, or by employing other people's labor through various means. Thus, the exact nature of the response does not depend solely on the environment, but on other social factors as well. For this reason the concept of stability must be expanded to embrace socioeconomic and management considerations. Three other sources of stability can be defined:

a. *Management stability*. Derived from choosing the set of technologies best adapted to farmers' needs and resource base. Initially, the application of industrial technology usually results in substantial increases in yield, as less and less land is left fallow and soil, water, and biotic limitations are bypassed. At the same time there is always an element of instability associated with the new technologies. The farmers are keenly aware of this, and their resistance to change often has an ecological basis.

b. *Economic stability*. Associated with the ability of the farmer to predict market prices of inputs and of the product and to sustain farm income. Depending on the sophistication of this knowledge, the farmer will make trade-offs between production and stability. To study the dynamics of economic stability in traditional agriculture, data must be obtained on total production, yields of important commodities, cash flow, off-farm income, net income, and the faction of total production that the farmer sells or trades.

c. *Cultural stability*. Dependent on the maintenance of the sociocultural organization and context that has nurtured traditional agroecosystems through generations. Rural development cannot be achieved when isolated from the social context, and it must be anchored to the traditions of local people. In order to fully understand the concept of stability, an integrated analysis must be adopted, since total stability results from the interplay of so many different causal factors.

4. Productivity is a quantitative measure of the rate of and the amount of production per unit of land or input. In ecological terms, production refers to the amount of yields or end product, and productivity is the process for achieving that end product. In ecological terms, production refers to the amount of yields or end product, and productivity is the process for achieving that end product. Yield per unit area can be one indicator of the rate and constancy of production, but it can also be expressed in other ways, such as per unit of labor input or per unit of cash investment or as energy efficiency ratios. When patterns of production are analyzed using energy ratios, it becomes clear that traditional systems are exceedingly more efficient than modern agroecosystems in the use of energy. A commercial agricultural system typically exhibits output/input ratios between 1 and 3, whereas traditional farming systems exhibit ratios from 10 to 15. Farms are both energy-consuming and energy-producing systems, but they also provide food, income, jobs, and a way of life for many agrarian societies. These are indexes that should be included in the overall evaluation.

In analyzing production/stability features of agroecosystems, it must be recognized that farmers have a fixed quantity of land, family labor, and capital with which to meet their subsistence goals, promote diversity of diet and income sources, minimize risks, maximize harvest security, and optimize returns under low levels of external inputs.

When the above indicators of performance are used to evaluate the viability of modern agroecosystems, it becomes apparent that although, historically, the introduction of new technology has greatly increased short-term productivity, it has also in the long term lowered the stability, sustainability, and equity of the total agricultural system. Today there is growing awareness of the social and environmental costs that are associated with large-scale, specialized production systems. Concerns include:

a. increased cost of, and dependence on, external inputs of chemicals and energy
b. decline in soil productivity from soil erosion and nutrient loss
c. contamination of surface and groundwater from fertilizers and pesticides
d. hazards to human and animal health and to food quality from agrochemicals
e. demise of family farms and local markets

When compared with traditional farming systems in developing countries, industrialized agricultural systems appear in the long-term more ecologically fragile and unsound (Fig. 1). In developing countries, small farmers place a higher value on reducing risk than on maximizing production. Through diversification and recycling, small farmers are usually interested in optimizing the productivity of scarce farm resources, not necessarily in increasing land or labor productivity. Also, small farmers choose a particular production technology based on decisions made for the entire farming system and not only for a particular crop. [*See* Farming Systems.]

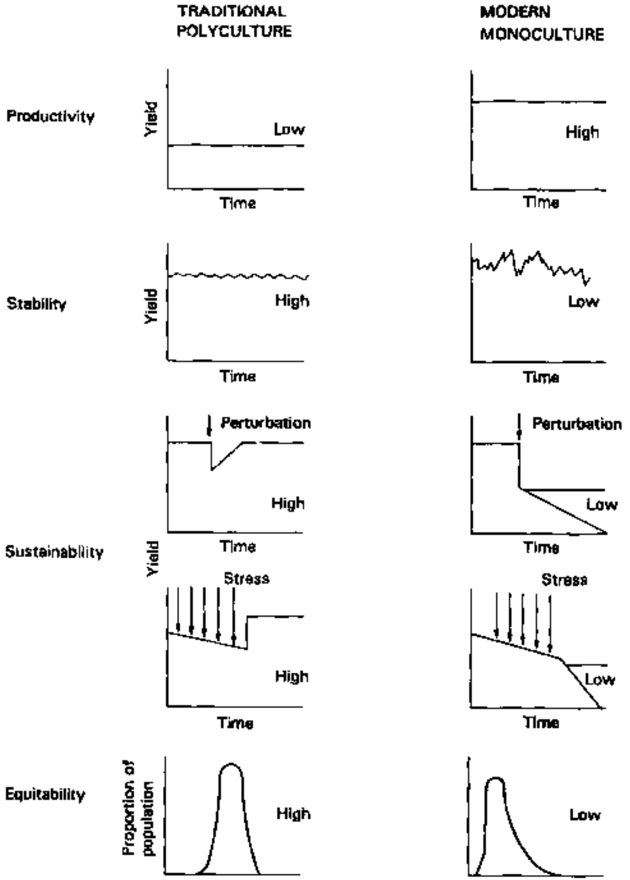

FIGURE 1 Long-term trends of ecological indicators in traditional versus modern agroecosystems.

II. Requirements of a Sustainable Agricultural System

Modern agriculture today faces the challenge of producing an economically viable crop while preserving the integrity of the local, regional, and global environment. The opportunities lie in the application of ecological theory to farm management. Agronomists must consider the interactions of all important biological and physical components of the cropping systems and must integrate this knowledge at the community level if they are to meet the twin challenges of economic growth and environmental sustainability. Agroecology is central to this integration of agronomy and ecology. Agroecology proposes that the basic tenets of a sustainable agroecosystem are the conservation of renewable resources, adaptation of the crop to the environment, and maintenance of a moderate but sustainable level of productivity. The production system must: (1) reduce energy and resource use and regulate the overall energy input so that the output : input ratio is high; (2) reduce nutrient losses by effectively containing leaching, run-off, and erosion and improve nutrient recycling through the promotion of legumes, organic manures and compost, and other effective recycling mechanisms; (3) encourage local production of food items adapted to the natural and socioeconomic setting; (4) sustain a desired net output by preserving the natural resources (by minimizing soil degradation); and (5) reduce costs and increase the efficiency and economic viability of small and medium-sized farms, thereby promoting a diverse, potentially resilient agricultural system. Table I describes the attributes of sustainable farming systems which rely on internal resources when compared to conventional systems that rely mostly on resources external to the farm.

As shown in Fig. 2 from a management viewpoint, the basic components of a sustainable agroecosystem include: (1) vegetative cover as an effective soil- and water-conserving measure, met through the use of no-till practices, mulch farming, use of cover crops,

TABLE I

Comparison of Ecological Characteristics between Conventional (External Input-Dependent) and Alternative (Internal Input-Dependent) Agroecosystems

	Alternative	Conventional
Sun	Main source of energy	Energy used as "catalyst" for conversion of fossil energy
Water	Mainly rain and small irrigation schemes	Increased use of large dams and centralized water distribution systems
Nitrogen	Collected from air by legumes and recycled	Primarily from synthetic fertilizer
Minerals	Released from soil reserves and recycled	Mined, processed, and imported
Weed and pest control	Biological and mechanical	With pesticides
Energy	Some generated and collected on farm	Dependence on fossil fuel
Seed	Some produced on-farm, local varieties	All purchased hybrids
Management decisions	By farmer and community	Some provided by agribusiness
Animals	Produced synergistically on farm	Feed lot production at separate locations
Cropping system	Rotations and diversity enhance value of all of above components	Monocropping
Labor	Most work done by the family living on the farm	Most work done by hired labor
Capital	Initial source is family and community; any accumulation of wealth is reinvested locally	Initial source is external indebtedness or equity, and any accumulation flows mainly to outside investments

etc.; (2) a regular supply of organic matter through the regular addition of organic matter (manure, compost) and promotion of soil biotic activity; (3) nutrient recycling mechanisms through the use of corp rotations, crop/livestock mixed systems, agroforestry and intercropping systems based on legumes, etc.; (4) pest regulation assured through enhanced activity of biological control agents, achieved by introducing and/or conserving natural enemies.

III. Restoring Biodiversity in Agroecosystems

Modern agriculture implies the simplification of biodiversity and reaches an extreme form in crop monocultures. The end result is the production of an artificial ecosystem requiring constant intervention. In most cases this intervention is in the form of agrochemical inputs which, in addition to boosting yields, result in a number of undesirable environmental and social costs.

As a consequence, modern agroecosystems are unstable and breakdowns manifest themselves as recurrent pest problems such as soil degradation and pollution of water systems. Worsening pest problems have been linked to the expansion of crop monocultures at the expense of vegetation diversity which, more often than not, provides key ecological services to ensure crop production and protection. Therefore a major concern in sustainable agriculture is the maintenance and/or enhancement of biodiversity and the role it can play in restoring the ecological balance of agroecosystems so that sustainable production may be achieved. Biodiversity performs a variety of renewal processes and ecological services in agroecosystems (Fig. 3), when they are lost, the costs can be significant.

A major strategy in sustainable agriculture is to restore agricultural diversity in time and space through crop rotations, cover crops, intercropping, crop/livestock mixtures, etc.

Some of the ecological features of these alternative cropping systems are:

a. *Crop rotations.* Temporal diversity incorporated into cropping systems, providing crop nutrients and breaking the life cycles of several insect pests, diseases, and weeds.

b. *Polycultures.* Complex cropping systems in which two or more crop species are planted within sufficient spatial proximity to result in competition or complementation, thus inhibiting or enhancing yields.

c. *Agroforestry systems.* An agricultural system where trees are grown together with annual crops and/or animals, resulting in enhanced complementary relations between farm components and increased multiple use of the landscape.

d. *Cover crops.* The use of pure or mixed stands of legumes or other annual plant species under fruit trees for the purpose of improving soil fertility, enhancing biological control of pests, and modifying the orchard microclimate.

e. *Crop/livestock mixtures.* Animal integration in agroecosystems aids in achieving high biomass output

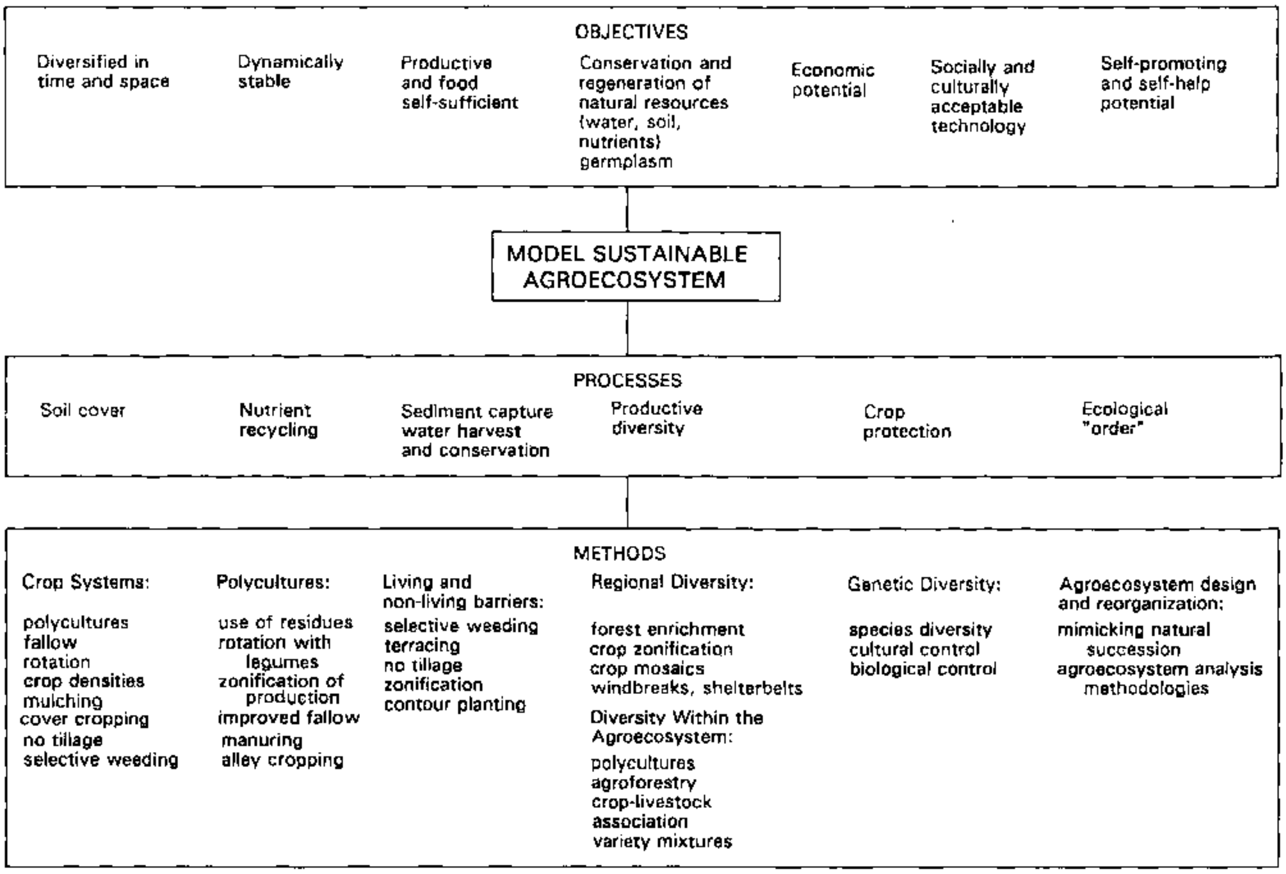

FIGURE 2 Objectives and processes in the design of a model sustainable agroecosystem.

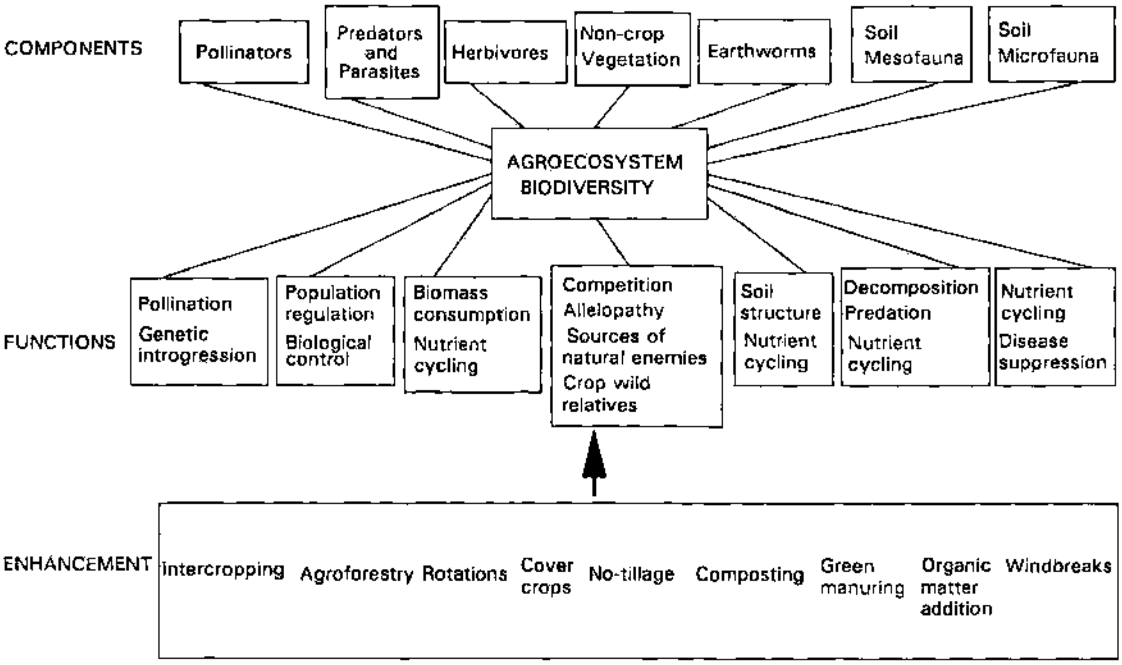

FIGURE 3 The integration of resources, components, and functions for multiple use farming systems.

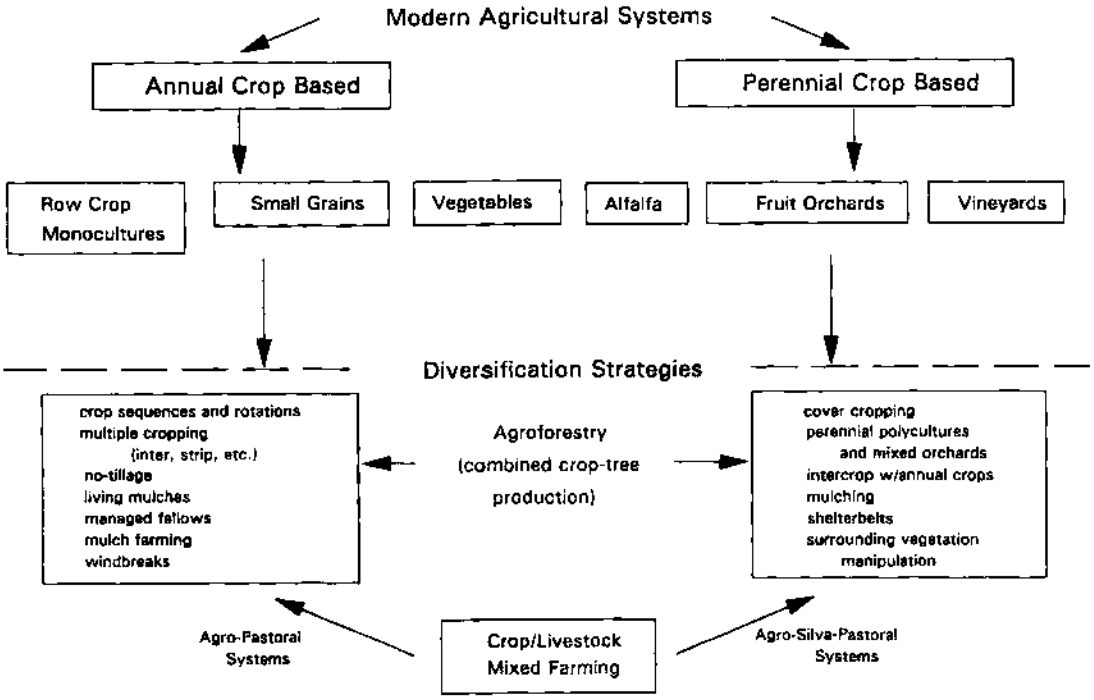

FIGURE 4 Diversification options for annual or perennial crop-based cropping systems.

within a given ecological and socioeconomic setting, complementing nutrient cycling, and optimizing management of pasture–crop rotations. As seen in Fig. 4, different options to diversify cropping systems are available depending on whether the current monoculture systems to be modified are based on annual or perennial crops. Diversification can also take place outside of the farm, in crop–field boundaries with windbreaks, shelterbelts, and living fences, for example, which can improve the habitat for wildlife and beneficial insects, provide sources of wood and organic matter, resources for pollinating bees, and, in addition, modify wind speed and the microclimate.

When biodiversity is restored to agroecosystems a number of complex interactions between soils, plants, and animals are established; the idea is to exploit complementary interactions and synergism that may result in beneficial results such as enhanced pest control, nutrient cycling, and soil conservation. When diversified cropping systems are assembled the possibilities of complementing interactions or "synergisms" between agroecosystem components are enhanced (Fig. 3), resulting in one or more of the following effects: (a) continuous vegetation cover for soil protection, (b) constant production of food, ensuring a varied diet and several marketing items, (c) closing of nutrient cycles and effective use of local resources, (d) soil and water conservation through mulching and wind protection, (e) enhanced biological pest control through diversification, (f) increased multiple use capacity of the landscape, (g) sustained crop production without the use of environmentally degrading chemical inputs.

IV. Biodiversity and Pest Management

Several studies have explored the relationships between vegetational diversity and pest reduction in diversified cropping systems (Fig. 5). The literature is full of examples of experiments documenting that diversification of cropping systems often leads to reduced pest populations. The studies suggest that the more diverse the agroecosystem and the longer this diversity remains undisturbed, the more internal links develop to promote greater insect stability. It is clear, however, that the stability of the insect community depends not only on its trophic diversity, but on the actual density-dependence nature of the trophic levels. In other words, stability will depend on the precision of the response of natural enemies (predators and parasites) to an increase in the population of herbivorous pests.

Although most experiments have documented insect population trends in single versus complex crop habitats, a few have concentrated on elucidating the nature and dynamics of the trophic relationships between herbivores and natural enemies in diversified agroecosystems. Several lines of study have been developed:

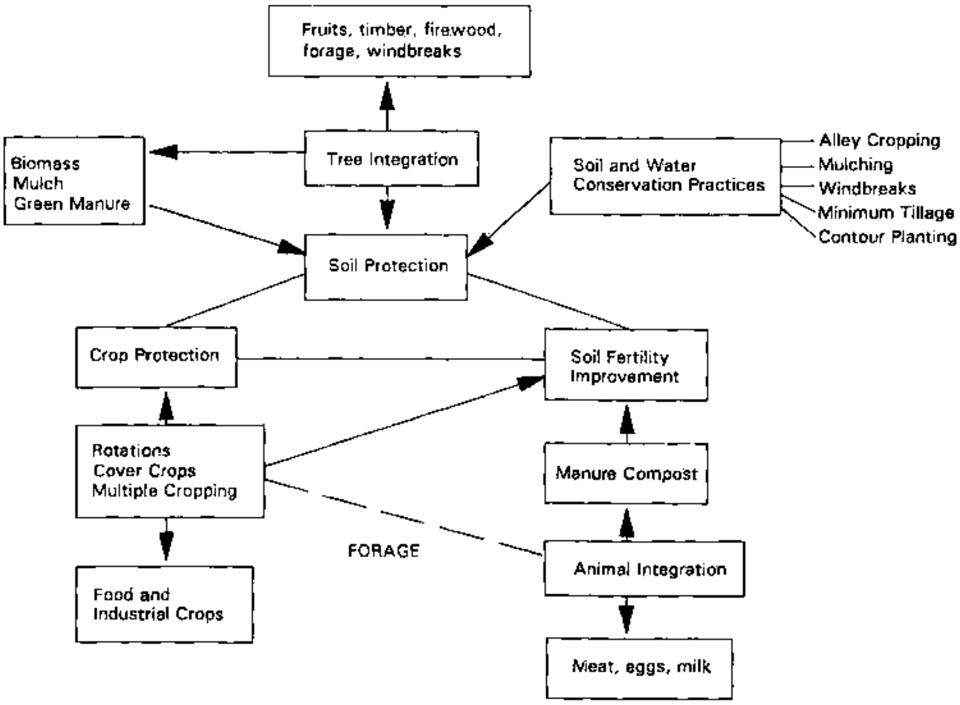

FIGURE 5 Complementary interactions in diversified cropping systems resulting in enhanced soil protection, soil fertility, and biological crop protection.

a. *Crop–weed–insect interaction studies.* Evidence indicates that weeds influence the diversity and abundance of insect herbivores and associated natural enemies in crop systems. Certain weeds (mostly Umbelliferae, Leguminosae, and Compositae) play an important ecological role by harboring and supporting a complex of beneficial arthropods that aid in suppressing pest populations.

b. *Insect dynamics in annual polycultures.* Overwhelming evidence suggests that polycultures support a lower herbivore load than monocultures. One factor explaining this trend is that relatively more stable natural enemy populations can persist in polycultures due to the more continuous availability of food sources and microhabitats. The other possibility is that specialized herbivores are more likely to find and remain on pure crop stands, which provide concentrated resources and monotonous physical conditions.

c. *Herbivores in complex perennial crop systems.* Most of these studies have explored the effects of the manipulation of ground cover vegetation on insect pests and associated enemies. The data indicate that orchards with rich floral undergrowth exhibit a lower incidence of insect pests than clean cultivated orchards, mainly because of an increased abundance and efficiency of predators and parasitoids. In some cases, ground cover directly affects herbivore species which discriminate among trees with and without cover beneath.

d. *The effects of adjacent vegetation.* These studies have documented the dynamics of colonizing insect pests that invade crop fields from edge vegetation, especially when the vegetation is botanically related to the crop. A number of studies document the importance of adjoining wild vegetation in providing alternate food and habitat to natural enemies which move into nearby crops.

The available literature suggests that the design of vegetation management strategies must include knowledge and consideration of (1) crop arrangement in time and space, (2) the composition and abundance of noncrop vegetation within and around fields, (3) the soil type, (4) the surrounding environment, and (5) the type and intensity of management. The response of insect populations to environmental manipulations depends upon their degree of association with one or more of the vegetational components of the system. Extension of the cropping period or planning temporal or spatial cropping sequences may allow naturally occurring biological control agents to sustain higher population levels on alternate host or prey and to persist in the agricultural environment throughout the year.

A classical example of the effects of diversity on pest populations is the role of the native blackberry bush (*Rubus* sp.) in vineyards of the Central Valley of California in the control of an important insect pest, the grape leafhopper *Erythroneura elegantula*. Long considered the key pest in many grape agroecosystems, this foliage-feeding leafhopper inflicts severe damage on vines and great losses in fruit yield when present in large numbers. Insecticides have often failed to give effective control of the leafhopper or their use has aggravated other pest problems, such as spider mites. Entomologists had known that the parasitic wasp, *Anagrus epos,* ovipositing in the eggs of the grape leafhopper kept the pest under control in some vineyards, but not in others.

The riddle was solved when it was realized that the wasp spent its winters parasitizing a different insect on *Rubus*. Since the leaves fall off grapevines in the winter and the grape leafhopper retreats to the edge of the vineyard and becomes inactive, the nonhibernating parasitic wasp has no shelter, food, or means of survival in this environment. Nearby blackberry bushes, however, keep their leaves during winter and host their own economically unimportant leafhopper species, *Dikrella cruentata,* all year round. When entomologists checked the eggs of this blackberry leafhopper, they found considerable parasitism by *Anagrus*. Thus, the weedy blackberry patches were providing a winter home for this important natural enemy of the key grape pest. Accordingly, it was growers with blackberry bushes in the vicinity of their vineyards who had the least grape leafhopper problems. *Anagrus* adults migrating back to the vineyards in the spring kept grape leafhopper numbers at low levels from the beginning of the season. Since this discovery, many growers have solved their major leafhopper problems with the planting of blackberry bush refuges in shady areas near their vineyards.

Recent studies in California have shown that prune trees planted next to vineyards allow early-season buildup of *A. epos*. After surviving the winter on an alternate host, the prune leafhopper, *Anagrus,* moves into the vineyard in the spring, providing grape leafhopper control up to a month earlier than in vineyards not near prune trees. Researchers now recommend that prune trees should always be planted upwind from the vineyard (but managed as a typical commercial prune orchard) and to plant as many trees as is economically feasible, since the more trees there are, the more productive the refuge is likely to be.

The beneficial effects of diversification are also evident in annual cropping systems. Strip cropping, a form of intercropping characterized by two or more alternate rows of crops, is common in the United States for corn/soybean. In California, cotton–alfalfa strip cropping has been tested for *Lygus* bug control with encouraging results. The effect of this system is that the alfalfa strips act as a trap crop when the invading *Lygus* colonize the cotton fields. Also, the strips serve as an insectary for natural enemies of other cotton pests. The natural enemies leave the alfalfa strip and enter the adjacent cotton to attack eggs and small larvae of the bollworm, cabbage looper, and beet armyworm.

In the coastal areas of Northern California, populations of cabbage aphids (*Brevicoryne brassicae*) and flea beetles (*Phyllotreta cruciferae*) can be significantly reduced in broccoli when this crop is grown intercropped with fava beans, wild mustard, vetch, barley, or with living mulches of various clover species. There are a number of other studies evaluating crop mixtures that exhibit reduced insect pest incidence. This reduction may be the result of an increased predator/parasitoid population, higher availability of alternate food for natural enemies, decreased colonization and reproduction of pests, chemical repellency, masking and/or feeding inhibition from nonhost plants, prevention of pest movement, and/or emigration and optimum synchrony between pests and natural enemies.

V. The Goal of Sustainable Agricultural Development

Sustainable agriculture refers to those forms of agriculture that:

1. Seek to optimize the use of locally available resources by combining the different components of the farm system, i.e., plants, animals, soil, water, climate, and people, so that they complement each other and have the greatest possible synergetic effects;
2. Seek ways of using external inputs only to the extent that they are needed to provide elements that are deficient in the ecosystem and to enhance available biological, physical, and human resources. In using external inputs, attention is given mainly to maximum recycling and minimum detrimental impact on the environment.

The central goal in sustainable agriculture is not to achieve maximum yield, but long-term stabilization. Sustaining agricultural productivity will require more than a simple modification of conventional management techniques. The development of self-sufficient, diversified, economically viable, small-scale agroecosystems comes from novel designs of cropping and/or livestock systems managed with technologies adapted to the local environment that are within a farmer's resources. At the farm, regional, and national level, sustainable agriculture implies the need for closely monitoring and carefully managing flows of nutrients, water, and energy in order to achieve a balance at a high level of production. Management principles include harvesting water and nutrients from the watershed, recycling nutrients within the farm, managing nutrient flow from farm to consumers and back again, using aquifer water judiciously, enhancing biodiversity, and using renewable sources of energy. As these flows are not confined by farm boundaries, sustainable agriculture requires management not only at farm level but also at district, regional, national, and even international levels.

Energy and resource conservation, environmental quality, public health, and equitable socioeconomic development should be considered in making decisions on crop species, rotations, row spacing, fertilizing, pest control, and harvesting. Many farmers will not shift to alternative systems unless there is a good prospect for monetary gain, brought about by either increased output or decreased production costs. Different attitudes will depend primarily on farmers' perceptions of the short-term and near-term economic benefits of sustainable agriculture.

It is crucial that scientists involved in the search for sustainable agricultural technologies be concerned about who will ultimately benefit from them. This requires recognizing that political determinants enter at the point when basic scientific questions are asked and not only at the time when technologies are delivered to society. Thus, what is produced, how it is produced, and for whom it is produced are key questions that need to be addressed if a socially equitable agriculture is to emerge. When such questions are examined, issues of land tenure, labor, appropriate technology, public health, research policy, etc. unavoidably arise. Increasingly scientists interested in promoting sustainable agriculture will have to become involved in meeting the adequate policy scenarios that promote sustainability.

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Swine Production

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Glossary

Barrow Male castrated before sexual maturity

Boar Male swine of any age

Finishing pig Young swine generally weighing more than 50 kg but not yet heavy enough for slaughter

Gilt Female swine of any age to second pregnancy

Growing pig Young swine after weaning, generally weighing less than 70 kg

Hog Swine of either sex, generally referring to immature gilts, barrows, or boars

Market hogs Finished hogs sold for slaughter

Pig In the United States, refers to young swine of either sex; in Europe, refers to all ages and either sex

Shoat Young weaned swine of either sex, generally weighing less than 50 kg

Slaughter pig Young swine ready for slaughter, usually weighing 90–130 kg

Sow Female swine having produced one or more litters

Stag Male castrated after reaching sexual maturity

Suckling pig Young swine before weaning

Swine Hoofed mammals of the family Suidae, genus *Sus*, species *scrofa* (*domesticus*)

Weanling pig Young swine after weaning

Swine production refers to that portion of animal agriculture devoted to the conversion of feed resources to pork. The enterprise varies from small "backyard" efforts in which household kitchen wastes and locally grown feedstuffs are fed to pigs to provide pork for home use to large highly specialized pork production systems geared for large commercial production. Pork production, regardless of the size of the enterprise, represents a major human food resource and requires inputs related to capital, labor, feed resources, physical facilities, disease control, waste management, marketing, and product quality assurance. The integration of all inputs and outputs into pork production systems at the farm, regional, national, and international level is an ongoing interdisciplinary effort.

I. Trends in Swine Production

Pork continues to occupy an important position as a food source in affluent societies as well as in developing countries with slower economic growth. The world swine population is growing at a faster rate than that of the human population; this is a reflection of the sustained demand for pork in all parts of the world. Total world meat consumption has continued to increase during the past decade to about 170 million tons in 1990 (32 kg/capita). Pork accounts for about 40% of total (70 million tons in 1990) and remains the first among all meat sources in total consumption, followed in descending order by beef, poultry, sheep, and goats.

A. Regional Distribution in the United States

Swine production in the United States continues to be concentrated in the Midwest where maize and grain sorghum production are concentrated, even though human population centers are remote from these areas. Of the approximately 80 million swine slaughtered annually in the United States, about 20 million are produced in the state of Iowa; the six states of Iowa, Illinois, Minnesota, Indiana, Nebraska, and North Carolina produce nearly two-thirds of the total pork in the United States. Other states ranking in the top 10 in swine production are Missouri, Ohio, South Dakota, and Kansas.

About three-fourths of the swine marketed in the United States are produced on farms raising more than 1000 head annually. This trend accompanies a steady reduction in the number of farms reporting swine.

B. World Distribution

The world swine population has increased steadily for many decades and in 1991 was approximately 860 million. China is the world's leading pork consumer and produces 35% of the world's pork. Differences among regions in animal reproductive rates and animal weights at slaughter result in discrepancies among countries between census figures and annual pork production. Asia has about one-half of the world's total swine, but produces about 40% of the world's pork; Europe (including the former USSR) has about 30% of the world's swine and produces 42% of the world's pork; corresponding figures for other continents are North and Central America, 12% and 14%; South America, 6% and 3%; Africa, 1.3% and 0.7%; and Oceania, 0.6% and 0.7%, respectively.

II. Pork as Human Food

A. Nutrient Composition

Pork, along with other meats, provides protein of higher nutritive value and mineral elements more efficiently used by the body than those present in most plants. Pork is an excellent source of some of the mineral elements and a poor source of others. For example, it is high in phosphorus, but almost devoid of calcium; it is high in potassium, but low in sodium; it is an excellent source of iron, and a good source of zinc, manganese, and magnesium. Also, pork is an excellent source of vitamins and, like other animal products, it contains vitamin B_{12} which is absent from plants. The nutrient content of pork and the percentages of the recommended daily vitamin allowance supplied by a 100 g (3 ounce) serving of cooked pork loin are summarized in Table I. [*See* MINERALS, ROLE IN HUMAN NUTRITION.]

TABLE I
Nutrients Contained in Pork

Nutrient	Amount
Protein	20.7%
Fat	6.9%
Water	71.5%
Minerals	0.9%
Calories	151 kCal of gross energy
Thiamin	1.13 mg/100 g (70% of daily adult requirement)
Riboflavin	0.33 mg/100 g (14% of daily adult requirement)
Niacin	6.8 mg/100 g (29% of daily adult requirement)
Vitamin B_6	0.50 mg/100 g (25% of daily adult requirement)[a]
Vitamin B_{12}	0.9 μg/100 g (20% of daily adult requirement)

[a] Based on raw fresh cut (about 85% of cooked value).

The long-term acceptance of pork as a major food source has been a result of its high nutritive value and the variety of processing and cooking methods available for its inclusion in many cultures. In many third world cultures, pigs kept to supplement family income are fed largely household waste and food gleaned locally and, in turn, provide a valuable source of protein, vitamins, and other nutrients to children and adults in an otherwise impoverished environment.

B. Properties Affecting the Acceptability of Pork to Humans

1. Pork Quality Factors

The amount of pork consumed in relation to alternative meat sources is dependent on cultural, religious, economic, and esthetic factors. Economic and esthetic forces, which are generally independent of cultural and religious constraints, are addressed briefly here. The share of the total market for animal products captured by pork is closely related to costs and supply of alternative sources, i.e., beef, lamb, and poultry, the production of which in turn, is driven by many of the same forces that control cost of production and marketing of pork. As world trade of food animal products has expanded, the economic factors determining the ultimate consumption of pork globally and in specific regions have become more complex. Esthetic aspects of pork as a food have a major impact on its acceptance. Pork is less variable than beef or lamb in recognized palatability factors (tenderness, juiciness, color, aroma, flavor) so that differences in age, breed, and environment have a relatively small effect on its quality. Color, firmness, and water-holding capacity are included together as a general appraisal of pork quality, ranging from pale, soft, exudative (PSE) to dark, firm, dry pork. Between these extremes is the most desirable. The pale color and excessive exudation of PSE pork creates merchandizing problems in the retail store. Recognition of the fact that PSE pork has a genetic basis has permitted the industry to reduce its incidence drastically by selection of animals free of this trait.

Much remains unknown about all of the factors involved in pork quality, the relative importance of each factor, and the degree to which pork acceptability can be controlled through husbandry practices, marketing and slaughtering procedures, and meat processing and technology. A major marketing constraint on the sale of pork from intact males is the objectionable odor and flavor perceived by some individuals. Fat-soluble male hormone derivatives such as 5-α-androst-16 ene-3-one, responsible for the "boar odor," are detected in most males by 6 months of age. Since boars grow faster, require less feed per unit of weight gain, and produce leaner pork than castrated males, there is economic incentive for their production. In some regions of the world, intact males are sold without price reduction to take advantage of their more efficient production, but in other regions, such as the United States, meat from intact males is discounted at the marketplace and sold as a component of sausage.

2. Health Factors

a. Fat Content and Composition Advances in swine breeding, feeding and management have transformed the composition of pork in the past 30 years to a relatively low-fat product. The average percentage of fat in pork in the United States is now about 7% of retail carcass weight compared with about 25% in the 1960s. This translates to a 50% reduction in caloric content of pork carcasses (300 kCal/100 g in the 1960s compared with a value of 150 now). Pork is relatively high in unsaturated fatty acids and its fatty acid composition resembles that of the diet fed to the animal. Thus, the stereotypic image of pork as a high-calorie food high in saturated fatty acids is erroneous. The cholesterol content of pork is about 70 mg/100 g, a value similar to that of beef and lamb and less than that of butter, cheddar cheese, eggs, and many seafoods. The digestibility of pork is high and contrary to myth, there is no evidence that pork fat (lard) differs from that of other animals and plants in digestibility by humans. [*See* FATS AND CHOLESTEROL, ROLE IN HUMAN NUTRITION.]

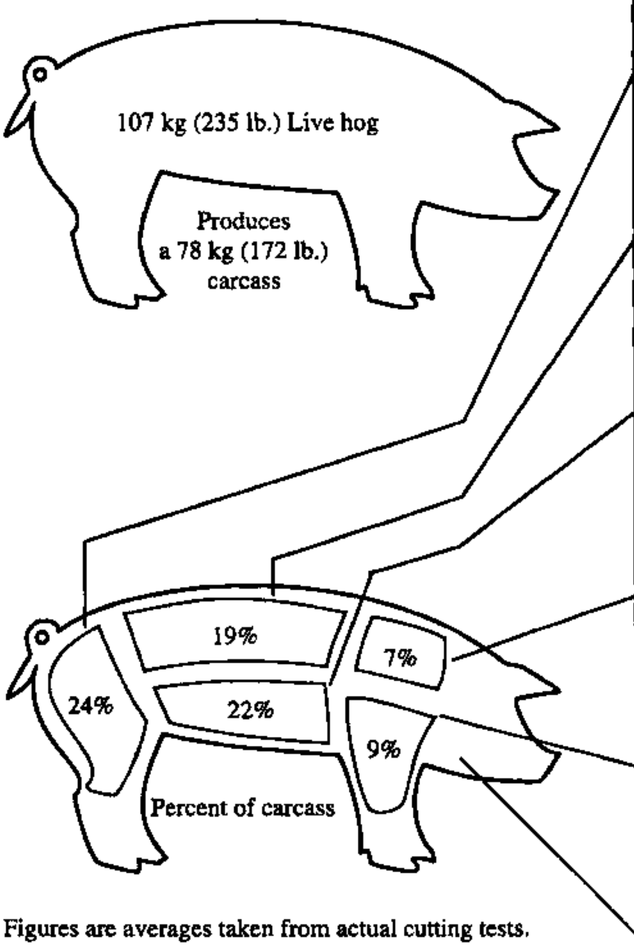
b. Disease organisms The parasite, *Trichinella spiralis*, may infect swine and cause trichinosis in humans consuming improperly cooked pork from infected animals. While still a serious potential health risk in many regions of the world, reliable methods of identification of infected animals have reduced the incidence of infection in swine to nearly zero in regions where swine production utilizes modern technology. Safe methods of killing the organism in infected pork (heating to 170°F, freezing for 20 days at 5°F, or subjecting the pork to high-energy radiation) have reduced the danger of infection drastically. Reported human cases of trichinosis in the United States number less than 100 annually, and effective drugs are now available for treatment.

Other infectious agents such as Salmonella and Campylobacter bacteria may contaminate pork and other food products, but public awareness of precautionary measures and careful practices of inspection and surveillance by federal and state agencies and by the industry itself of animal and carcass handling and processing en route to the consumer provide a dependable supply of safe and wholesome pork.

C. Wholesale and Retail Cuts of Pork

The proportion of the live animal that is available as edible lean meat is often referred to as "percent lean cuts." These lean cuts are the shoulder (Boston butt plus picnic), loin, and ham. The lean cuts constitute 40% or more of the weight of typical market weight swine, but more than 75% of the value under U.S. pricing conditions. The lard yield from a U.S. No. 1 market pig is about 10% of the retail carcass weight in pigs in the United States now, compared with 35% forty years ago and 16% twenty years ago. About 50% of the weight of a 78-kg carcass is made up of the wholesale cuts [ham, loin, shoulder and side (spare ribs and cured bacon)]; the remainder is skin, fat, jowl, tail, feet, and trimmings. [*See* ANIMAL BY-PRODUCTS FROM SLAUGHTER; MEAT PROCESSING.]

Carcasses also yield important organs such as brain, liver, and kidney. The wholesale cuts, showing the location of each component on the carcass, are illustrated in Fig. 1. Methods of carcass breakdown and nomenclature vary in different countries and regions, but the same general approaches are used in separating and merchandizing the various cuts in all markets. Regions also vary in the choice of cuts that are processed into cured products, e.g., bacon in the United States is from the belly, while bacon in Canada and Europe is often from the shoulder. In many places within the developing countries, constraints on postslaughter handling are imposed by lack of modern abattoirs and refrigeration and inadequate dis-



Figures are averages taken from actual cutting tests.

Carcass data vary, depending on cutting method and type of hog.

CARCASS BREAKDOWN

	Retail Pork* Kg(Lbs)	Other Products Kg(Lbs)	Carcass Total Kg(Lbs)
Ham , 18.4 kg (40.6 lbs)			
Cured ham	10.5(23.1)		
Fresh ham	0.8(1.7)		
Trimmings	2.3(5.1)		
Skin, fat, bone		4.8(10.7)	
Total	13.6(29.9)	4.8(10.7)	**18.4(40.6)**
Loin 14.6 kg (32.1 lbs)			
Blade roast	3.3(7.4)		
Center chops	7.3(16.0)		
Sirloin roast	3.2(7.0)		
Fat		0.8(1.7)	
Total	13.8(30.4)	0.8(1.7)	**14.6(32.1)**
Side, 16.9 kg (37.3 lbs)			
Cured bacon	8.6(19.0)		
Spareribs	3.1(6.8)		
Trimmings	4.3(9.6)		
Fat		0.9(1.9)	
Total	16.0(35.4)	0.9(1.9)	**16.9(37.3)**
Shoulder			
Boston Butt, 5.5 kg (12.2 lbs)			
Blade steaks	0.9(2.1)		
Blade roast	0.6(1.3)		
Cured butts	3.6(0.8)		
Trimmings	0.4(0.8)		
Total	5.5(12.2)		**5.5(12.2)**
Picnic, 7.4 kg (16.4 lbs)			
Arm roast	1.5(3.3)		
Cured picnics	2.2(4.9)		
Trimmings	2.2(4.8)		
Skin, fat, bone		1.5(3.4)	
Total	5.9(13.0)	1.5(3.4)	**7.4(16.4)**
Miscellaneous, 15.2 kg (33.4 lbs)			
Jowls, feet, tail neckbones, etc.	4.1(9.0)		
Trimings	4.2(9.3)		
Fat, skin, bone		5.5(12.1)	
Shrink and loss		1.4(3.0)	
Total	8.3(13.8)	6.9(15.1)	**15.2(33.4)**
TOTAL	63.1(139.2)	14.9(32.8)	**78.0(172.0)**

* Retail cuts on semi-boneless basis. Fully boneless would show lower retail weight

FIGURE 1 Wholesale cuts of pork. [Reprinted, with permission, from "Meat and Poultry Facts, 1993." American Meat Institute.]

tribution systems. In these areas, meat from freshly killed swine is sold immediately, with little effort directed toward identifying and separating conventional wholesale cuts.

III. Life Cycle and Physiological States

The generation interval in swine is about 1 year. The early sexual maturity, prolificacy, and short gestation period of swine compared with other food animals, and the associated high heritability of the traits involved, make possible relatively rapid changes in growth efficiency and body composition. Females and males reach puberty at about 6 months of age and can be mated by 8 months of age to produce a litter at about 1 year of age (gestation is 114 days). Average number of pigs born per litter is 9–12 and an average of 8–10 pigs are weaned at 3 to 5 weeks of age. After weaning, pigs are usually full fed a nutritionally complete diet throughout the growing–finishing period of about 4 months at which time they are marketed for pork or retained as breeding animals (5 to 6 months of age). Lactating sows do not normally ovulate during the suckling period, but within 1 week after their pigs are weaned, they will ovulate and become receptive to the male. Mating at this first postweaning estrus usually results in a pregnancy, and a second litter is born 3.9 months later. Therefore, it is common for one sow to produce 2–2.5 litters of 8–10 market weight pigs yearly, weighing an average of 230 pounds per pig (total of 3680 pounds of live weight) at 5 to 6 months of age.

A. Body Size and Growth

Eleven-day-old embryos begin to show signs of attachment to the endometrium. However, true implantation to form the placenta does not occur until about Day 18 (embryo length of 5–10 mm). By Day 20 the crown–rump length is about 10 mm and the fetus can be used for gross laboratory study. From this stage onward, the rate of fetal growth is tremendous. From a crown–rump length of 2.5 cm and weight of 1.5 g at 30 days, the fetus grows to a crown–rump length of 30 cm (12 times the 30-day length) and a weight of about 1200 g (800 times 30-day weight) at birth. The number of developing fetuses is inversely related to the weight of individual fetuses at term. Viable young have been known to weigh as little as 400 g and more than 2000 g at birth after a normal gestation. The newborn pig contains about 82% water, 12% protein, 5% minerals, and 1% fat.

The body weight during the 4- to 5-week suckling period doubles during the first week and is six to ten times the birth weight by 4 weeks. Postweaning growth is plotted in Fig. 2 and body protein accretion during the same period (64 to 154 days of age) for females, males, and male castrates is shown in Fig. 3. Changes in body composition of genetically obese, lean, and contemporary swine from 10 weeks to 24 weeks of age are depicted in Fig. 4. The steady increase in fat accretion is evident in animals of all three genotypes. The greater protein deposition of intact males than of females and of females than of castrates emphasizes the effect of sex hormones on patterns of growth and ultimate carcass value of swine. Unresolved problems with boar odor (see previous section) in intact males has precluded the widespread capture of their increased lean meat production.

Animals are marketed at 5 to 6 months of age weighing 220 to 240 pounds. Those retained for breeding are normally placed on limited feed intake to avoid excessive fatness. By breeding age of 8 months, females weigh 260 to 300 pounds and males weigh 280 to 320 pounds. Body weight and skeletal size continues to increase until 3 years of age or beyond, despite restricted feed intake after market weight is attained. Mature females often weigh in excess of 500 pounds and mature boars may reach 800 pounds or more, depending on how liberally they are fed after maturity.

B. Reproduction and Lactation

A high reproductive rate is essential in a successful swine enterprise. Knowledge of the anatomy and physiology of male and female reproductive tracts is important for maximization of reproductive efficiency. The reproductive tract and endocrine control of reproduction of female and male swine share the same general features as those of other mammals. The female reproductive tract includes two ovaries, fallopian tubes, uterus (consisting of the body and two uterine horns), cervix, vagina, and vulva. The uterine horns are long and tortuous to accommodate numerous developing fetuses. In the mature sow, they may be 1 m or more long when extended. The ovaries are lobular, owing to follicles in varying stages of development. There may be 10 to 25 individual mature follicles. Puberty (onset of estrous cycle, i.e., first ovulation) occurs at about 6 months of age in most breeds, although in some Chinese breeds it occurs at less than 4 months. Puberty, which coincides

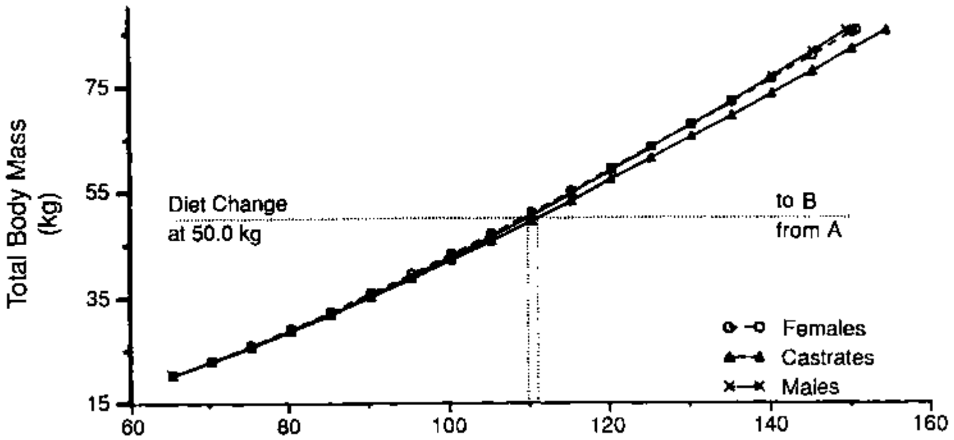


FIGURE 2 Empty body weight curves (live body weight minus gastrointestinal tract contents) of contemporary crossbred female, male, and castrated male pigs from age 64 to 154 days as generated by computer simulation. [Reprinted from Pomar *et al.*, (1991). *J. Animal Science* **69,** 1468–1488.]

with first estrus and sexual receptivity, is influenced by season of the year, social environment, and degree of spacial confinement. Relocation or exposure to a boar consistently advances puberty. The number of ova released per estrus increases gradually over the first several estrous cycles. There is a large range even among normal animals kept under adequate husbandry, partly due to breed differences. Although age at puberty is several months, the number of ova available for release in the course of a lifetime, determined in prenatal life as oogenesis, is complete by Day 100 after conception. The estrous cycle length (onset of one estrus to the onset of the next) is important from the standpoint of planning breeding dates. Length of the cycle averages 21 days (range is about 18–24 days). During proestrus (1–3 days), females are alert to the approach of the boar, will mount other females, and accept mounting by diestrus females, but will not tolerate mounting by a boar. During estrus, the swollen vulva and vaginal discharge first observed during late proestrus are accompanied by restlessness (fence-walking, agitation), mounting of other animals, and acceptance of the boar. The female in estrus will mate for a period of 2–3 days, and because ovulation lasts over several hours, mating on two successive days of estrus often results in birth of larger litters owing to improved synchrony of contact between newly released ova and spermatozoa. Since the estrous cycle is under endocrine control, it can be altered by exogenous hormones. Technology, including the use of prostaglandins in combination with reproductive hormones and

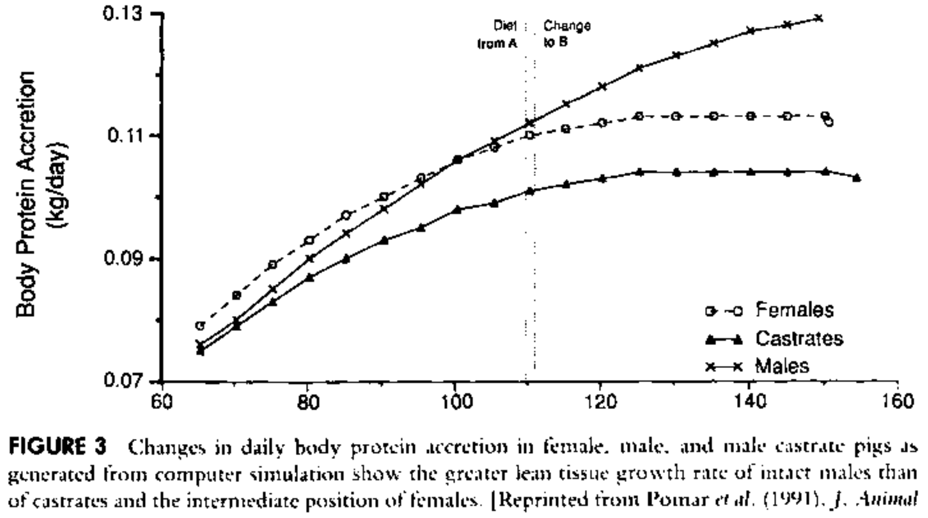


FIGURE 3 Changes in daily body protein accretion in female, male, and male castrate pigs as generated from computer simulation show the greater lean tissue growth rate of intact males than of castrates and the intermediate position of females. [Reprinted from Pomar *et al.* (1991). *J. Animal Science* **69,** 1468–1488.]

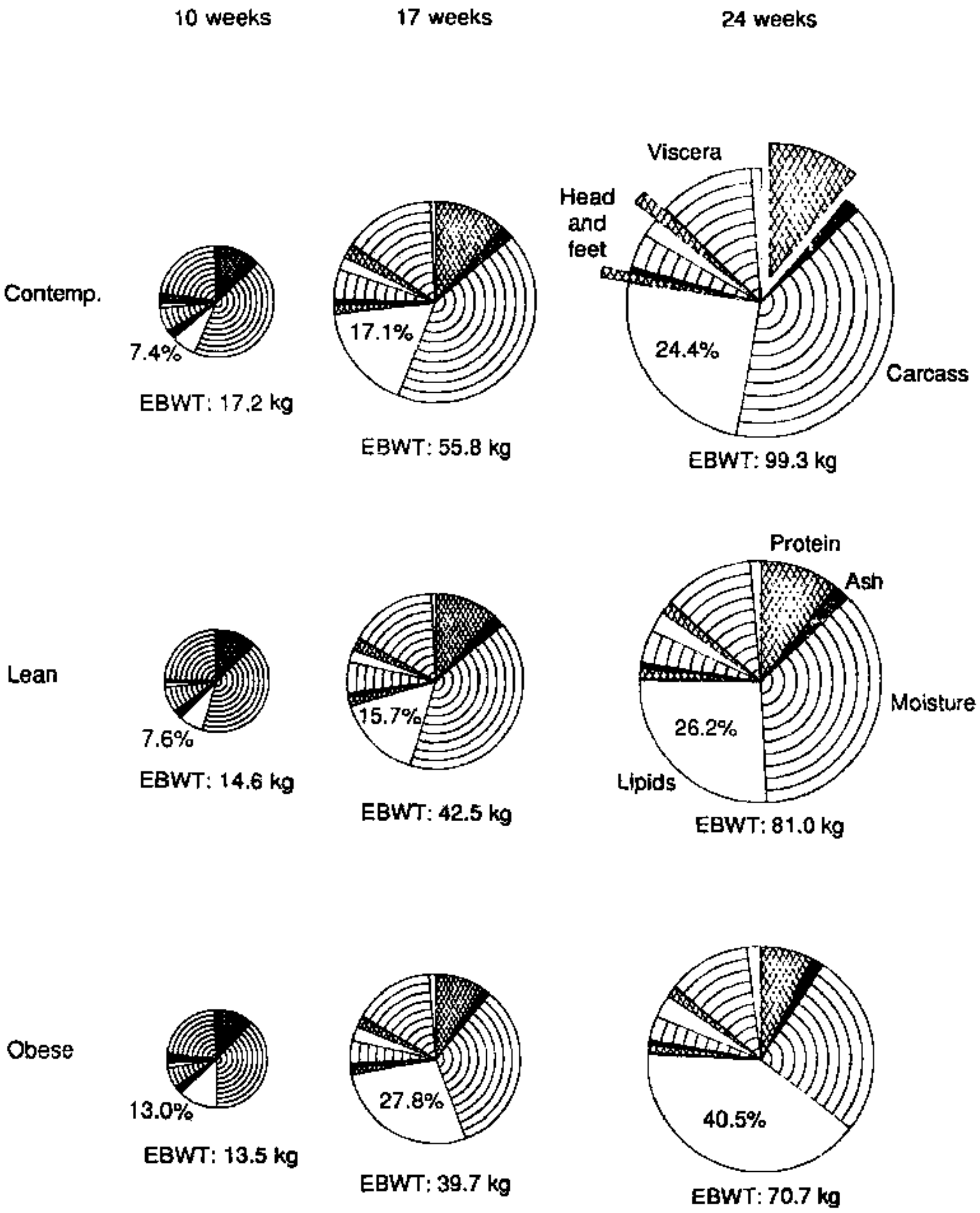


FIGURE 4 Changes in body composition with increasing age in pigs of different genetic background. Percentages shown are for carcass lipids as a fraction of empty body weight (EBWT). [Reprinted, with permission, from *Pork Production Systems*, (1991). Van Nostrand Reinhold, NY]

their derivatives, is available to apply these therapies in commercial swine production, particularly as a means of using artificial insemination for genetic improvement and for tighter control of reproduction schedules in individual enterprises. Artificial insemination in concert with estrous cycle synchronization has not been widely applied to date in the swine industry owing more to economic considerations than to technical limitations. [*See* Animal Reproduction, An Overview of the Reproductive System; Animal Reproduction, Male; Animal Reproduction, Nonpregnant Female; Animal Reproduction, Pregnancy.]

Males produce viable sperm by about 4 months of age, but generally are not used for breeding until they have attained larger size and mature sexual behavior at 6–8 months of age. The male reproductive tract of swine includes all of the typical accessory organs of the mammal. The testes migrate out of the body cavity to the scrotum at about 100 days of prenatal life. The tail of the epididymis forms a cap over the dorsal end of the testis. In normal castration, the epididymis and the attached tunica vaginalis are removed with the testes. Stored sperm leave the epididymis via the vas deferens. The seminal vesicle, Cowper's (bulbourethral) gland, and prostate gland all contribute to semen volume, which may exceed 500 cc per ejaculate. Ten or more sows can be inseminated from a single ejaculate. Techniques for freezing semen for use in artificial insemination are available. Modern genetic evaluation procedures are expected to stimulate the commercial use of this technology. As superior boars are identified, the opportunity to extend their use to more sows and more herds will be enhanced by artificial insemination.

Prenatal deaths occur in 30–40% of developing young between Days 1 and 114 of gestation. More than half of these losses occur during the first 25 days and most of the remainder occur before midgestation. Mummified fetuses represent deaths that occur after 40 days and are differentiated from stillborn pigs by partial resorption. The causes of these large prenatal losses are not fully understood, but limited uterine capacity and high ovulation rate have been identified as two distinct but interrelated major components of the problem. The transfer of swine embryos from the uterus of one female to that of another is a useful tool as a means of increasing the number of progeny obtained from genetically superior animals. Another option with potential application is the manipulation of embryonic cells in culture which can then be cloned and inserted into the embryo. International transfer of swine germplasm by these approaches offers advantages over traditional transportation systems.

Lactation provides the means by which essential nutrients and immunological protection reach the neonate. The immune protection of colostrum (mammary secretion during the first days of lactation) is more critical in swine than in many other animals. Placental transfer of immune antibodies is almost nil, leaving colostrum as the principal source of neonatal protection against pathogenic agents. The normal duration of lactation in swine is 6–8 weeks, but nutritional needs of the rapidly growing pig exceed those provided in milk after about 3 to 4 weeks, because the peak of lactation is reached at about 4 weeks. Therefore, pigs are usually weaned at 3 to 5 weeks and the sow enters postweaning estrus within a few days and can be mated to produce another litter. Milk production efficiency in swine is very high and nutrient yield per unit body weight in highly productive sows is greater than that in dairy cattle (sow milk contains nearly 20% dry matter compared with 12% in cattle). [*See* LACTATION.]

Newborn piglets begin suckling immediately and do so at hourly intervals over the 24-hr day and thereafter throughout lactation. Daily milk yields of 6 kg have been recorded over an 8-week lactation (288 kg total). Milk yields of 5 to 10 kg daily with an energy concentration of 1.2 kcal per kg are expected in lactating sows and are partly dependent on the number of nursing pigs. This high level of production allows rapid growth of piglets during the first few weeks of postnatal life. Systems of early weaning are available in which the pig is weaned at 1 or 2 days of age to a liquid formula containing milk products. Growth approaching or exceeding that obtained with sow-reared littermates can be achieved, but only if frequency of feeding and amount consumed at each meal approximate sow-rearing conditions. Such early-weaning programs allow the possibility of rebreeding the sow earlier than normal to maximize the total pigs produced per calendar year. The economics of such a program will be affected by the relative prices of sow feed versus milk-replacer formula and differences in the efficiency with which nutrients are partitioned for milk production, maternal nutrient stores, and piglet growth.

IV. Genetics and Breeding Systems

The genetic aspects of the swine production system set both the limits and potential for performance of the system. Breeding stock selection systems have evolved as a means of accelerating genetic improvement from the traditional visual appraisal approach to modern computer-based performance testing and genetic evaluation procedures. The wide genetic diversity of swine is evidenced by the large number of breeds and groupings in different regions of the world of swine having unique characteristics and appearance. There are currently probably more than 100 recognized breeds and more than twice as many genetic groups of swine with traits unlike those of other groups. This vast number of gene combinations provides the basis for animal breeders to capitalize on the plasticity of swine to improve biologic efficiency and animal vigor and to create populations of swine to meet human needs most effectively. Representative breeds and types of pigs are illustrated in Fig. 5. Early breeders of purebred swine contributed to changes in animal performance and appearance through livestock shows and fairs and advertising. In this form of breeding, producers kept replacement females from young animals to replace older breeding animals being culled. Replacement boars were purchased from other breeders as a means of introducing new genes. As the merits of crossbreeding became evident as a means of improving productivity (the term heterosis or "hybrid vigor" was introduced to describe the greater than expected improvement in a given performance trait in the offspring of crossbred swine than in those of offspring of swine of the same breed), the swine industry of the United States adapted the approach by the producers of rotating two or more breeds to provide replacement breeding stock. Various crossbreeding systems have evolved from the original systems, e.g., rotational crossing, terminal crossing, rota-terminal crossing, all aimed toward improved breeding stock. Genetic improvement by selection for specific heritable traits has been affected by the development of performance testing programs (both central and on-farm). The rate of genetic improvement in any particular trait is determined by four factors: intensity of selection, accuracy of selection, genetic variability for the trait, and generation interval. Progress can be relatively rapid for most heritable traits in swine because of the short generation interval (1 year) and the wide genetic variability in most of the economically important traits, i.e., growth rate, body leanness, and efficiency of feed utilization. Significant development of statistical procedures has gone into modern genetic evaluation of swine breeding stock. Procedures such as the swine testing and genetic evaluation system (STAGES) are used to assist purebred breeders in evaluating their swine and in decisions related to their individual breeding plans. As such systems are accepted and used by the industry, the theory of quantitative genetics finds valuable practical application. [*See* ANIMAL BREEDING AND GENETICS.]

Rapid advances in molecular biology have created new opportunities for genetic improvement in swine. The functional basis for genetic variation in economically important traits, such as growth and lactation, relates to hormones, enzymes, and various intracellular processes. Progress is underway in elucidating the genetic code for directing synthesis of specific proteins. It is possible to trace segregation of genetic factors previously not observable as they are transmitted between generations. However, the complexity of the processes complicates progress, because many DNA combinations code for many different proteins involved in the many body processes. The location and identification of simple genetic codes for major proteins ultimately will allow greater manipulation of these major genes. Recombinantly derived hormones and other metabolites are already used to enhance lean growth and production. As an example, porcine somatotropin produced from *Escherichea coli* bacteria is effective in increasing leanness and is safe for use in swine production. Transgenic animals produced by these transfer techniques have also been produced, e.g., transgenic swine with high somatotropin production; however, associated changes in other metabolic processes in these transgenic animals have discouraged commercial application of the technology to date.

V. Nutrition and Feed Formulation

Feed represents 55–85% of the total cost of commercial swine production, depending mainly on the relative costs of feed, labor, and housing in a particular case. Therefore, the formulation of nutritionally balanced diets must be based on selection of economical as well as nutritious feed ingredients. Swine have a digestive system with limited ability to utilize cellulosic and other fibrous feeds; therefore, they are in direct competition with humans for available food supplies. The degree of competition is related to cultural differences in food preferences. For example, wheat and potatoes are not usually fed to swine in the United States, as the demand for human consumption holds the price too high, but in other parts of the world these crops are commonly fed to swine. Similar relationships exist for other crops in other parts of the world. [*See* FEEDS AND FEEDING.]

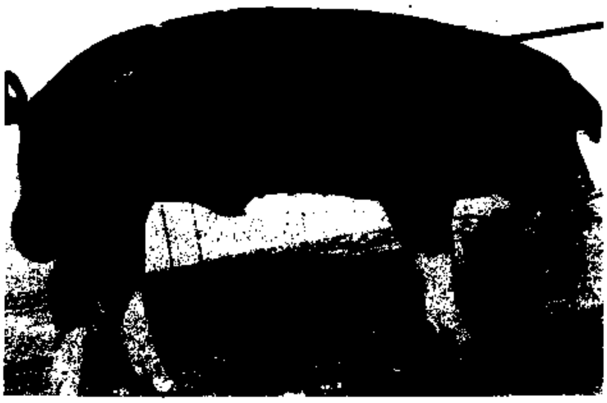
A. Nutrient and Energy Requirements

Nutrient (defined as any chemical entity required by the animal to meet metabolic needs) and energy requirements for swine correspond closely with those required by humans. The known requirements of swine follow:

Water.

Fatty acids. Linoleic and arachidonic acid are required and some fat (0.06% of diet) is needed for absorption of fat-soluble vitamins.

Protein. Proteins are probably not required as such, except in neonates who receive immune proteins intact from milk; the ability to absorb these proteins from the intestinal tract lumen is lost during the first 2 days after birth. Of approximately 25 amino acids in nature, the following are considered indispensable for swine because they are not synthesized from other metabolites in body tissues and therefore must be included in the diet: arginine (for growth only), histidine, isoleucine, leucine, lysine, methionine (50% replaceable by cystine), phenylalanine (30% replaceable



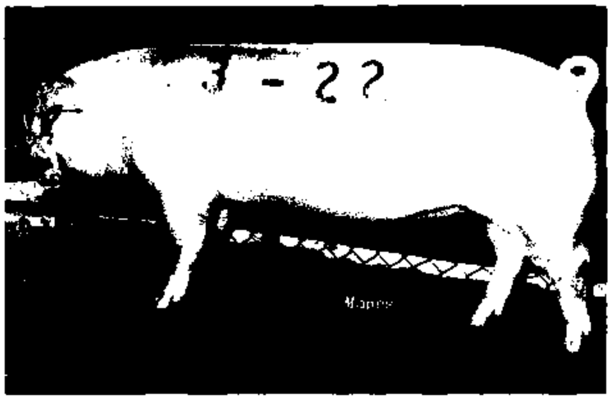
Poland China boar

Chester White barrow

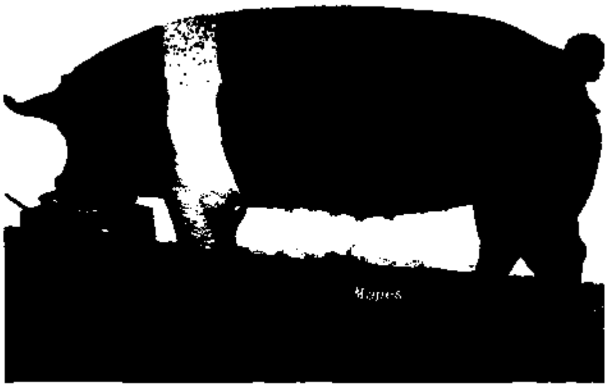
Spotted boar

Miniature sow

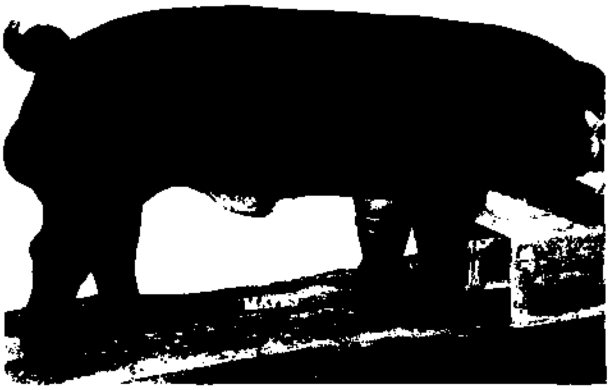
Yorkshire boar



Landrace gilt

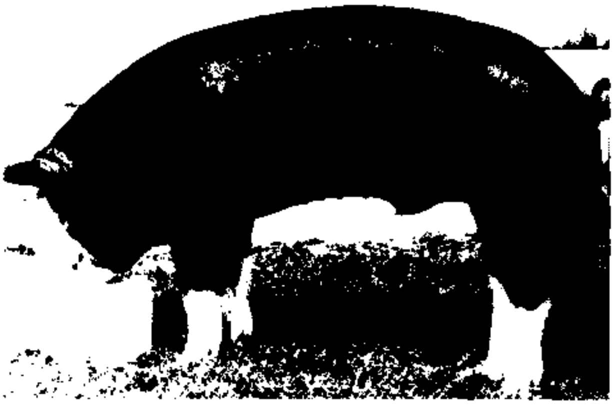


Hampshire gilt



Duroc boar

FIGURE 5 Breeds and types of swine



Berkshire boar

Pietrain gilt

Ming sow (China)

Jinhua gilt (China)

Meishan boar (China)

Ningxiang boar (China)

FIGURE 5 *Continued*

by tyrosine), threonine, tryptophan, and valine. The remaining amino acids are considered dispensable (nonessential) because they are synthesized in the body from nonspecific sources of nitrogen and other metabolites. Thus the total protein requirement can be met by including adequate amounts of all of the indispensable amino acids plus sufficient nonspecific sources of nitrogen in the diet to synthesize the nonessential amino acids.

Energy (Calories). Calories can be supplied by fat (9 Cal/g) or carbohydrate (4 Cal/g) or by the breakdown of protein (5 Cal/g).

Fat. Although the caloric density of fat is about 2.25 times that of carbohydrates, most swine feeds are high in carbohydrates and low in fats.

Carbohydrate. There is no proof that carbohydrates are required as a source of energy, but since all natural feedstuffs contain some carbohydrate, it becomes an academic question. If a dietary requirement exists, it is as glucose.

Vitamins. The fat-soluble vitamins are A, D, E, and K. The water-soluble vitamins are biotin, choline (replaceable by methionine), folic acid, niacin (nicotinic acid), pantothenic acid, riboflavin, thiamin, vitamin B_6, vitamin B_{12}, vitamin C (ascorbic acid), inositol, and paraaminobenzoic acid (PABA). Biotin and vitamin K requirements are normally met by microbial synthesis in the large intestine, but when coprophagy is prevented, as in swine raised in confinement in slatted floor pens, deficiencies have been reported. Vitamin C synthesis in the body normally meets the metabolic requirement for the vitamin, except in young pigs exposed to the stress of early weaning.

Inorganic Elements. Elements required in large amounts (major elements) include calcium, magnesium, phosphorus, potassium, sodium; elements required in small amounts (minor elements) include: chlorine, cobalt (as a constituent of vitamin B_{12}), copper, iodine, iron, manganese, selenium, sulfur (as a constituent of sulfate, and of thiamin, methionine, cystine, and several other organic compounds), and zinc.

[*See* Animal Nutrition, Nonruminant; Animal Nutrition, Principles.]

B. Life-Cycle Feeding

The quantitative nutrient requirements differ for each productive function, i.e., growth, pregnancy, lactation, and maintenance. The daily amount of swine feed is adjusted to accommodate the special requirements of each physiological stage, and the composition of the diet is changed to match the physiological needs at each stage. The protein (amino acid) requirement, expressed as a percent of the diet, is highest in the neonate and declines gradually with age. Growing swine are normally fed *ad libitum,* so the protein concentration in the diet is reduced as body weight increases and concentrations of other nutrients are also adjusted downward during the growing period. Expression of nutrient requirements as a percent of diet allows the formulation of diets designed to meet all nutrient requirements for growth when the diet is offered *ad libitum*. In mature animals, body weight must be controlled to avoid obesity by limiting daily feed allowance, except in lactation. Lactating sows require large energy intake to accommodate adequate milk production and are normally fed *ad libitum*.

Commercially prepared diets are formulated to meet specifically defined periods of the life cycle: gestation, lactation, preweaning, growing period (early postweaning), finishing period (late postweaning), and nonpregnant, nonlactating females, and males.

C. Feedstuffs

A broad array of feed resources is available worldwide from which to formulate balanced diets for all stages of the life cycle. Feedstuffs can be classified broadly according to their major contribution of nutrients to the total diet.

Energy sources. Carbohydrates are the most abundant form of energy in plants and, as such, are the most widely available sources of energy for swine feeding. Grains and their by-products are the most important sources of carbohydrates. Each of these sources of energy also supplies important amounts of protein, vitamins, and inorganic elements. The major grains used in swine feeding are corn (maize), sorghum (milo), barley, oats, rye, wheat, triticale, rice, and their distillery and milling by-products. The amounts of these by-products available in a particular region are governed by the way in which the respective crops are utilized for human consumption. For example, rice, the most important crop in Asia, is a staple food for billions of people, but a variety of by-products of the milling process supplies large quantities of rice bran and screenings for swine feeding. Likewise, wheat bran and other seed coat fractions are available as by-products from the milling process for swine feeding in the United States. Roots and tubers, including cassava and potatoes, as well as bananas, plantains, sugar beets, and their products are major sources of energy for swine feeding in many regions and cane molasses, citrus and citrus pulp, and many other high-carbohydrate plant materials are used in swine production throughout the world. Household kitchen wastes and food discarded from hotels, restaurants, and institutions contribute additional amounts of energy and other nutrients to swine production. Animal fats, including tallow, lard, and fish oils as well as vegetable fats from such plants as coconut, soybean, cottonseed, maize, safflower, sesame, and others, are by-products of other food and industrial uses and are used in swine feeding.

Protein sources. Next to energy, protein is the nutrient class needed by swine in the largest amount. A wide variety of protein sources is available from both plants and animals.

Animal proteins. By-products of abattoirs include meat meal, meat and bone meal, blood meal, fish meal, shrimp meal, krill meal, hatchery waste, feather meal, and animal and poultry wastes, while dried whey comes from cheese plants. All are utilized in swine feeding.

Plant proteins. Oilseed meals are the most important plant proteins in swine feeding. These meals are by-products of plant oils extracted for human consumption. Soybean meal is by far the greatest source of plant protein used in the United States and in many parts of the world. Other important plant protein supplements resulting from fat extraction are coconut meal, cottonseed meal, linseed meal, peanut meal, canola meal, rubberseed meal, safflower meal, sesame meal, and sunflower meal. Several grain legumes provide significant amounts of protein used in swine production. These include whole soybeans, dry beans, kidney beans, mung bean, lima bean, chick pea, cow pea, pigeon pea, and field pea; their use for swine is normally confined to sources not meeting standards for human consumption. Legumes whose vegetative parts are used for swine feeding include alfalfa and sweet lupin.

Single cell protein (SCP). Single-cell protein sources, i.e., algae, bacteria, fungi, and yeast, are undergoing thorough investigation for nutritional value and safety for human and animal consumption. Some of these SCPs are grown on such hydrocarbons asn-alkenes and methanol. Others, e.g., yeast and fungi, are grown on sulfite-waste liquor, a waste product of the wood pulping industry. Blue-green algae, *Arthrospira platensis*, can be grown successfully on swine effluent. All of these SCP sources are high in well-balanced protein and can be produced in large quantities on waste materials or by-products of other processes.

Synthetic amino acids. For many years the feed industry had pure lysine and methionine available from microbiological production at prices competitive for use in swine feeds in limited amounts. Now, gene-splicing techniques are available to mass-produce these and other amino acids microbiologically. These breakthroughs in biotechnology should provide the basis for greater use of synthetic amino acids and a reduction in conventional plant and animal protein use in future swine production.

Inorganic element and vitamin sources. Most energy and protein sources provide some vitamins and inorganic elements but usually it is necessary to balance the diet with specific sources of these essential minor ingredients. Common salt is added to almost all swine diets as a source of sodium and chloride. Calcium and phosphorus sources include bone meal and products such as dicalcium phosphate and rock phosphate; oyster shell, limestone, and gypsum are common sources of calcium, but devoid of phosphorus. Most plant energy and protein sources are marginal or deficient in calcium and the phosphorus is present largely as phytic acid phosphorus which is poorly utilized by swine. Therefore most swine diets must be supplemented with both elements. Other inorganic elements usually deficient in common ingredients are iodine, iron, selenium, and zinc. Commercially formulated swine feeds usually contain inorganic salts of these trace elements plus manganese and copper to ensure against deficiency. Synthetic sources of vitamins provide the opportunity to supplement swine diets with pure vitamins to supplement those provided in energy and protein sources used in the diet. Inclusion in the diet of a variety of feedstuffs of plant and animal origin made it possible in earlier times to avoid serious vitamin and inorganic element deficiencies, before the identities and metabolic functions of these nutrients were recognized. In general, animal products and green forages are good sources of vitamins and minor elements. As swine production has moved to confinement rearing, the opportunity for ingestion of these essential nutrients from forages and soils has decreased, adding to the importance of dietary supplementation with pure sources of these nutrients.

VI. Swine Diseases

Many infectious, metabolic, and nutritional diseases affect swine. Some of the infectious diseases, e.g., brucellosis, leptospirosis, erysipelas, and tuberculosis, are of particular significance because the organisms are pathogenic to humans. All of these zoonoses are treatable in humans; their importance in swine production makes their control of high priority. Metabolic and nutritional diseases of swine, although of less importance from a public health standpoint, require continued surveillance in herd health programs. [*See* ANIMAL DISEASES.]

A. Infectious Diseases

The practice of veterinary medicine has gradually evolved from a major focus on treatment of diseases in individual animals to emphasis on preventive herd health maintenance in which the veterinarian and swine producer work together in applying modern principles of disease prevention and control. The common infectious diseases of swine are generally divided into bacterial, viral, and mycoplasmal diseases. Important bacterial diseases include Haemophilus infections, causing pleuropneumonia, polyserositis, and arthritis; Pasteurella pneumonia; Bordetella infections, causing respiratory diseases, including atrophic rhinitis (whose etiology may also involve Pasteurella and possibly other agents); tuberculosis; swine dysentery; salmonellosis; colibacillosis; mastitis; erysipelas; leptospirosis; brucellosis; streptococcal diseases; anthrax; and clostridial infections. Important viral diseases include swine influenza, transmissible gastroenteritis, pseudorabies (Aujeszky's disease), hog cholera, African swine fever, swine pox, porcine adenovirus, porcine enterovirus, porcine cytomegalovirus, foot-and-mouth disease (aftosa), swine vesicular disease, vesicular stomatitis, vesicular exanthema, porcine rotavirus; rabies, reovirus, congenital tremors, encephalomyocarditis, porcine endemic diarrhea, Japanese encephalitis, porcine parvo virus infection, and swine infertility and respiratory syndrome (SRIS). Important mycoplasmal diseases include Mycoplasma pneumonia, Mycoplasma arthritis and Mycoplasma polyserositis.

Internal and external parasites impede productivity in the absence of appropriate control programs. Small intestinal parasites, *Ascaris suum* (roundworm), *Strongyloides ransomi* (threadworm), and *Trichinella spiralis* (trichina); large intestinal parasites, *Trichuris suum* (whipworm), *Oesophagostomum* spp. (nodular worm); and lung (*Metastrongylus* species) and liver (*Fasciola hepatica*) parasites all adversely affect swine health. They can be controlled by judicious use of anthelmintics and by good sanitation. Common external parasites are *Sarcoptes scabiei* (sarcoptic mange mite) and *Haematopinus suis* (louse). These parasites are controlled by external application of insecticides or by systemic application of ivermectin which also controls internal parasites.

Improvement of animal performance through disease control is increasingly recognized as an important component of efficient swine production. Control and treatment by medication is costly. Acquired immunity is achieved for protection from many infectious diseases by vaccination and other forms of immunization. New approaches to vaccine production, such as vaccines produced by recombinant DNA (gene splicing) technology, are available, e.g., foot-and-mouth disease vaccine and pseudorabies vaccine, and others should be forthcoming.

Swine producers, particularly those involved in purebred or seedstock production, routinely introduce new breeding animals into their herds. These introduced animals are potential sources of infectious disease. For each specific pathogen, choices must be made for the best control program to preserve herd health. Many herds are derived and maintained as SPF (specific pathogen-free) enterprises by removing pigs from the mother by surgery and raising them in laboratory conditions before their introduction into the herd as future breeding stock in order to break the infection cycle for many pathogens. Breeding stock is not the source of all pathogens; many pathogens are transmitted by rodents, birds, people, and even by feed, dust particles, and aerosol suspensions. Traffic control even to the point of requiring employees and visitors to shower and change clothes before entry into the facility is becoming commonplace in large swine production facilities.

B. Metabolic and Nutritional Diseases

Swine are affected by a large array of metabolic disorders of importance in commercial pork production. Some of these, including gastric ulcers, osteoporosis, osteochondrosis, photosensitization, and porcine stress syndrome (PSS), have their counterpart in humans and other animals, and result in significant economic losses. Genetic and environmental variables share in contributing to these disorders, and husbandry and feeding may modify their incidence and severity. Marginal levels of one or more nutrients are contained in most homegrown feedstuffs not fortified with commercial sources of vitamins, mineral elements, and protein. These marginal deficiencies are manifested as reduced growth or efficiency of feed utilization, often so slight as to go unrecognized.

Frank deficiencies of several specific nutrients are associated with specific typical clinical signs, e.g., zinc (parakeratosis), iron (baby pig anemia), selenium, and vitamin E (hepatosis dietetica, mulberry heart disease), calcium, phosphorus, or vitamin D (osteoporosis, rickets), calcium–phosphorus imbalance (fibrous osteodystrophy), and niacin (necrotic enteritis). Toxic effects of specific nutrients are of some practical concern, e.g., skeletal abnormalities in newborn piglets from sows fed excess vitamin A during early gestation; calcification of soft tissues in pigs fed excess vitamin D or diets containing plants that contain active metabolites of vitamin D; liver damage and death in pigs fed excess copper commonly fed to promote growth.

Mycotoxins (toxic metabolites of several fungi that commonly infect grains and oilseeds) are a serious threat to swine reproductive function and growth of young pigs. Contaminated feed can be fed safely only if diluted with uncontaminated feed or by the inclusion in the diet of agents such as zeolites and other aluminosilicate minerals that may decrease the absorption of the toxins from the digestive tract.

VII. Production Systems

Swine production has evolved to be a primary enterprise on many farms as a means of converting processed feedstuffs and breeding stock resources into marketable pork products. The concept of a "systems approach" analogous to the production of goods in other industries has become important in commercial pork production. Modern production often occurs in environmentally controlled facilities with automated feed delivery and manure disposal (Fig. 6). This technology requires highly skilled personnel and careful record keeping and cost accounting. The major controllable inputs are the breeding system, the breeding stock, the feedstuffs, and the formulated diets. The output from the production system determines the

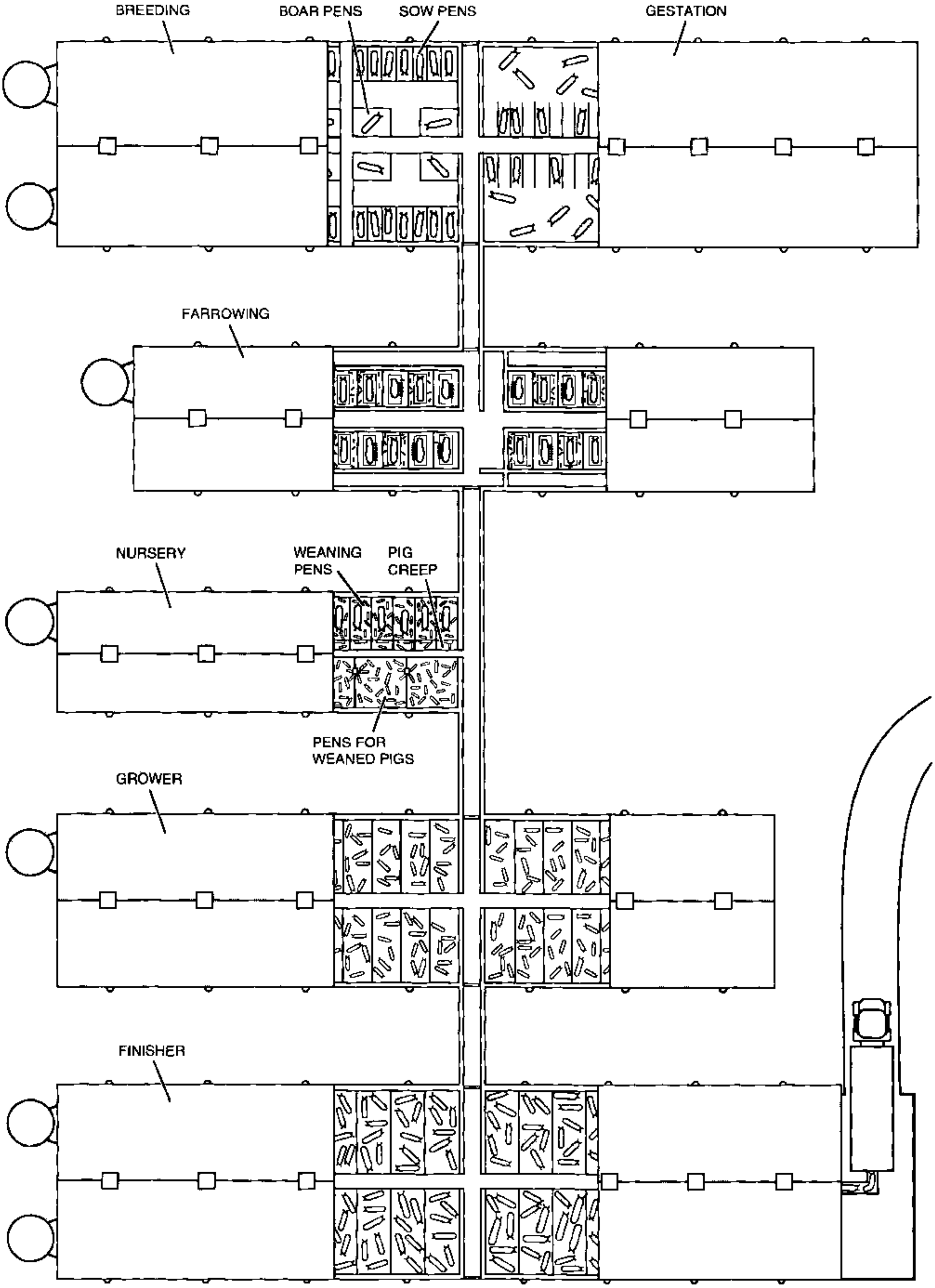


FIGURE 6 Environmentally controlled total confinement unit keeps pigs indoors throughout the life cycle. [Reprinted, with permission, from Scientific American, May, 1983.]

income to offset costs and possibly a margin of profit for the enterprise. Income is determined by number of animals marketed, weight of each animal, and value (price received) per unit weight. Thus, briefly stated, the profitability of the enterprise is determined by the efficiency of the production system in integrating the inputs and outputs to maximize efficiency and overcoming the effects of extraneous factors such as climate and disease. Environmentally controlled facilities and effective disease control programs have evolved in response to the need to minimize the impact of these variables on animal productivity.

Life-cycle feeding systems that address the changing nutritional requirements of swine during specific stages of growth, reproduction, and lactation, coupled with least-cost diet formulation by computer, have been developed. Also, the application of genetic principles to select for economically important heritable traits, e.g., lean tissue growth, feed utilization, reduced fat accretion, and reproductive efficiency, has been integrated into the plan and design of pork production systems.

Management of the pork production system requires appropriate approaches to the execution of the plan (construction and adaptation of physical facilities, financial arrangements, labor supply, feed formulation and delivery, manure disposal, genetically defined breeding stock, swine husbandry, market outlet); adjustment to unforeseen occurrences (changes in feed supplies or costs, changes in market prices or options, disease outbreaks, availability of new technology); problem identification; and problem resolution.

The accumulated knowledge acquired over many years of research on the reproductive and growth biology of the pig has provided a data base to allow the collection of the knowledge in the form of a set of computer programs to simulate the numerous alternative courses of action in pork production and predict the likely outcome. These computer simulation models, together with management information systems, provide potential support to the manager's decision making. Such computerized systems, termed integrated decision support systems (IDSS), currently are in use in several countries in research aimed toward guiding pork production.

VIII. The Future of Swine Production

A. Consumer Demand for Pork

The demand for pork among consumers in the United States has increased in proportion to population growth during the past 50 years; in 1992, 7.8 million metric tons of pork were produced to meet the per capita demand for approximately 31 kg. Although the United States ranks third, behind Mainland China and the European Community (which includes Belgium, Luxembourg, Denmark, France, West Germany, Greece, Ireland, Italy, Netherlands, Portugal, Spain, and United Kingdom) in annual pork production (Table II), imports of pork in 1992 exceeded exports (29,300 and 185,000 metric tons, respectively). This importation put the United States third behind only West Germany and the former Soviet Union in total pork imported among countries of the world.

Pork consumption in other parts of the world continues to increase, particularly in developing countries where per capita incomes are improving and stimulating greater consumption of animal products. Per capita consumption of pork in 1992 was highest in Denmark (65.8 kg), followed by Sweden, Poland, Germany, Spain, and Hungary, all with consumption greater than 40 kg per capita; by Taiwan, Hong Kong, Singapore, France, Canada, and the United States, with values between 30 and 39 kg; and by the United Kingdom, China, Japan, Korea, Australia, and the former Soviet Union, with values ranging from 15.6 to 18.5 kg. Mexico and Brazil consumed 9.5 and 6.9 kg per capita, respectively, and all other countries consumed less. Projections by the United Nations of human population growth indicate that total population will, except for the most conservative scenario, equal or exceed 10 billion by 2030.

Swine production is closely tied to grain consumption, which is by far the largest single component of global agriculture. Global consumption of all grains

TABLE II

Top 10 Pork-Producing Countries in Thousand Metric Tons, 1992[a]

1. China, Mainland	26,330
2. European Community—12[b]	13,735
3. United States	7,816
4. Former Soviet Union	4,875
5. Poland	1,998
6. Japan	1,430
7. Canada	1,200
8. Brazil	1,150
9. Taiwan	1,120
10. Mexico	830

[a] Carcass weight equivalent.

[b] European Community—12 includes Belgium–Luxembourg, Denmark, France, Germany, Greece, Ireland, Italy, Netherlands, Spain, United Kingdom, and Portugal.

has grown at an annual rate of 1.6% since 1979. It is assumed that this rate will continue to 2030, resulting in a doubling of total consumption of grains (human food and animal feed) to 3.3 metric tons in 2030. More than 90% of the total growth in grain consumption is projected to be in the developing countries, mostly in Asia. The coarse grains, e.g., maize, sorghum, and millet, are projected to increase more rapidly (3.2%) than the principal food grains, i.e., wheat (2.3%) and rice (1.3%). The reason is the high income elasticity of demand for meat and other animal products, for which the coarse grains are feedstuffs. Increased land area devoted to coarse and food grain production and increased yields per hectare will be required to meet these projected needs. Ultimately, the long-term future of swine production likely will be determined not only by the degree to which pork is preferred in the diet relative to alternative foods, but by constraints imposed by agronomic, ecological, economic, and demographic forces external to biological characteristics of the pig.

B. Animal Performance

For the foreseeable future, animal performance will improve for most of the relevant traits of economic importance in pork production. This seems predictable, based on rapidly developing technology in all aspects of biology and engineering, e.g., recombinant DNA technology for production of nutrients, vaccines, and metabolic modulators; genetic manipulation including advanced methods in population genetics and in transgenics; application of nutrient repartitioning agents such as porcine somatotropin and β adrenergic agonists to improved growth, lactation, and reproduction; new vaccines and other disease control procedures; refinements in design and management of pork production systems that maximize production; and marketing efficiency. As the knowledge base of nutritional requirements for each phase of the life cycle enlarges, further refinements will be made in tailoring nutrient intake to age, gender, genetic makeup, and body composition.

The use of recombinant DNA technology will hasten the cost-effective substitution of individual amino acids into the diet at appropriate levels and combinations to enhance efficiency of growth and will save significant amounts of traditional high-protein supplements. Recombinant DNA techniques also will find increased application in the production of hormones, digestive enzymes, growth factors, and other metabolites to be administered in the feed or other delivery systems, e.g., subcutaneous implants to improve lean tissue growth. As the use of nutrient repartitioning agents such as porcine somatotropin and β adrenergic agonists increases, the resulting improvement in lean tissue accretion will stimulate reevaluation of the nutrient requirements of these animals and may signal a further increment of improvement in overall pork production efficiency. Females and males may be housed separately during the finishing period and diets specially tailored to their differing nutrient needs will be fed. As technology for suppressing secondary sex characteristics (objectionable odor in the meat) of intact boars is refined, the use of boars rather than castrates for pork production will be common in the United States as it already is in many other countries to capture the innate superiority of the intact boar to the male castrate in growth rate and lean tissue production.

The development and use of nonconventional and newly identified sources of energy and protein from plants and animals for use in feeding swine will continue, and such crops as grain amaranth, several seed legumes, and forages may find greater use. Blue–green algae, yeasts, and bacterial cells grown in culture may be genetically engineered to produce feed resources with specific desired nutritional composition. As the knowledge of intestinal microbial populations and large intestine physiology in the pig expands, greater utilization of feedstuffs high in lignocellulose and other fermentable substrates may be forthcoming. The identification of new microbes with high cellulose-splitting ability that thrive and compete well in the milieu of the large intestinal environment may create the opportunity for new feeding strategies in areas where conventional high-concentrate feedstuffs are scarce or expensive due to their high demand for human consumption.

C. Animal Well-being

Societal concerns about the well-being of animals have escalated in recent years and these concerns have engendered heightened attention by food animal producers to the impact of production practices on their animals. Practices that have received the most attention in animal agriculture are those related to space and restricted movement. In swine production, the restraint of sows in gestation stalls and farrowing crates has been brought into question in this regard. Farrowing crates first came into use as an effective means of protecting piglets from injury and death caused by crushing or overlaying by the mother. This and most other husbandry practices were developed to reduce costs of production and improve the comfort and productivity of the animal. It has become increasingly accepted by pork producers and others associated with the industry that pigs (and other farm animals) are sentient creatures with the capacity to suffer; it follows that those working with pigs have a moral responsibility for their welfare, a concept accepted by most pork producers for many years. The Farm Animal Welfare Council of the United Kingdom in 1993 described the five freedoms of farm animals (including pigs) as freedom from hunger, thirst, and malnutrition; freedom from discomfort; freedom from pain, injury and disease; freedom to express normal behavior; and freedom from fear and distress. Implicit in this description is the acceptance of the moral responsibility to provide pigs with a reasonable quality of life and a humane death. This implies obligations for ensuring well-being during all of life, including transit to slaughter and death itself.

It is clear that the sustainability of pork production, aside from resource-related constraints, will in the long term be determined by consumer acceptance of pork. The degree of acceptance will be determined by consumer perceptions not only of the product itself, but of the conditions under which it was produced, including an assurance of acceptable animal well-being.

Limited knowledge concerning the impact of the environment and husbandry practices on animal well-being has curtailed an effective response by swine producers to the concerns raised by those who have challenged the acceptability of current production practices. Research funding to answer biological questions of animal well-being is now emerging and several important questions need to be addressed: What are the scientific measures of swine well-being? How do the behaviors of swine vary in different environments? How are their responses affected by genetic and environmental factors? How do animals utilize different amounts and kinds of space in relationship to group size and composition? What are the appropriate indicators of stress, pain, and suffering, and how are they measured? All of these and many more researchable questions must be addressed to provide adequate information for fair and informed legislative decisions and sound public education. Issues of animal well-being will continue to receive greater attention by researchers, consumers, and producers as intensive pork production systems become more prevalent around the world.

D. Environmental Stability and Ecological Balance

Swine production, like all of animal agriculture, must be approached in such a way as to promote environmental stability and ecological balance. Intensive swine production potentially may have negative effects on the environment. Odors produced by swine formerly went relatively unnoticed, but encroachment of agricultural areas by human activities, e.g., residential expansion, has created concerns about air pollution; pollution of water by swine waste run-off must be controlled by appropriate design and placement of intensive swine production facilities. A major agricultural impact on water quality originates from crop production which requires fertilization of soils with inorganic and organic (manure) materials and the use of herbicides and pesticides. Broad awareness of these problems has awakened efforts to devise systems of swine production that eliminate the negative impact of these practices on the environment, e.g., efforts to reduce the use of chemical pesticides and herbicides by genetic manipulation of plants to improve resistance to insect pests and diseases, advanced methods of manure management, and nutrient preservation to reduce nitrates in the water supply. [*See* ANIMAL WASTE MANAGEMENT.]

Tillage and irrigation practices have contributed to soil erosion and water pollution, and a conflict between agriculture (including pork production) and the human population for use of available water. Soil and water conservation programs and cropping practices, e.g., irrigation, cropping methods, and pasture and range management, must be tied closely with swine production methods, e.g., waste management, feed resource allocation, and facilities design. The needs and goals of swine production must be adapted to fit on a local and global basis within the broad context of agriculture, forestry, rangeland, and animal ecological systems and must adapt to demographic changes in the human population. The interrelationships among swine production, production of other animals and crops, and the human population in competing for available resources must be tuned in the future, more than ever before, to the preservation of environmental quality and ecological balance. The maintenance of this delicate balance is attainable if the research needed to improve swine production systems and provide sound information at all levels for informed decisions can be done and the information can be effectively transmitted.

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Tariffs and Trade

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Glossary

Countervailing duty Tariff imposed by the importing country in response to export dumping by exporters (i.e., the exporter either sells below cost of production or sells abroad at a price below that charged in the home market)

Large-country tariff One which can make the importer better off. Because there is a "terms of trade effect," the producer gain plus the government revenue effect is larger than the consumer cost in the case of an optimal tariff

Optimal-revenue tariff Set by the government to maximize government tariff revenue from imports; this tariff has the effect of restricting trade even more than for the optimal large-country tariff

Small-country tariff One which makes the importing country worse off since the producer gain plus the government revenue collected from the tariff is smaller than the consumer cost of the tariff due to higher prices

Tariff Policy instrument which drives a price wedge between what the exporters receive and what the importer pays

Tariffs and Trade can be defined as a branch of economics dealing with the theory and measurement of international protection. The theory applies to manufacturing as well as to agriculture; however, the empirical content of this article applies only to agriculture. From theory, one can easily deduce why certain producers and other special interest groups lobby for tariffs.

Almost every nation protects its industries from foreign competition. One such protectionist instrument is the tariff. This is an instrument used by importers of a specific commodity; it drives a wedge between export and import prices. For example, if a country imposes a dollar per pound tariff on beef imports then, excluding all other factors such as transportation costs, the price in the exporting nation is one dollar below the price producers receive in the importing country. Often the term "duty" is used interchangeably with the concept of tariff, and these terms will be used interchangeably in this discussion. First, we explore the theory of tariffs and then examine some empirical data relating to their importance. Tariffs are widespread. Especially in agriculture, tariffs—along with certain nontariff barriers such as quotas—have, for many years, stalled global trade negotiations under the General Agreement on Tariffs and Trade (GATT).

I. Tariff Theory

There are many types of tariffs. Those of major importance are discussed below and are: small-country tariffs, large-country tariffs, optimal-revenue tariffs, general equilibrium tariffs, countervailing duty, effective tariff rates, and scientific tariffs.

A. Small-Country Tariffs

The following demonstration assumes that a small-country importer can impose a tariff without affecting the price charged by the exporter. Norway, for example, can establish tariffs and quotas on apple imports without affecting the prices charged for apples by exporting countries. The following demonstration is based on this assumption. In Fig. 1 the supply for apples is S while the demand is D. At a world free-trade price of P_w, the nation imports Q_1Q_2 of apples; domestic production is Q_1 while consumption is Q_2.

Suppose the country imposes a tariff of size T. What are the effects? (1) Price rises in the importing country from P_w to P_1. (2) Internal production increases from Q_1 to Q_1'. (3) Demand decreases from Q_2 to Q_2'. (4) Imports are reduced to $Q_1'Q_2'$. As a result of the tariff, producers in the importing country gain (measured by area P_1abP_w), consumers lose (measured by area $P_1a'b'P_w$), and the government gains tariff revenue (measured by area R or $aa'dc$). As measured in conventional economic terms, there is a net cost from the tariff of the two cross-hatched areas ($abc + a'b'd$).

As with many of the demonstrations to follow, tariffs benefit producers in importing countries along with the agra-business complex that both sells inputs to agriculture and markets the final product. This is why producers and the entire agra-business complex lobby (and are usually quite successful) for tariff protection. [*See* MACROECONOMICS OF WORLD AGRICULTURE.]

B. Large-Country Tariffs

Large countries may affect export prices when they impose tariffs. For example, as a major importer of fresh grapes, the United States might well force down the export price of grapes from Chile by increasing the tariff as demand in the United States falls. This can result in net economic gains in the importing country. Consider Fig. 2. Suppose a tariff of t^0 is introduced. Unlike the small country case, the export price is affected by the tariff. The price facing the importing consumer increases, causing demand to drop; however, if the price facing the exporter remained the same and the export supply was unchanged, an export surplus would be created. Because the exporter's excess supply schedule (which shows the amount available for export at various border prices) is upward sloping, the price must drop to P^* to equate supply and demand in the exporting country. [*See* PRICES.]

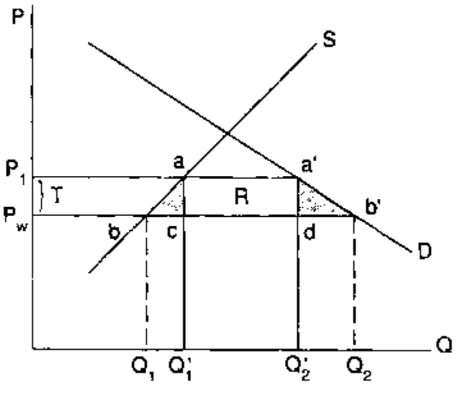

FIGURE 1 Tariffs in the small-country case.

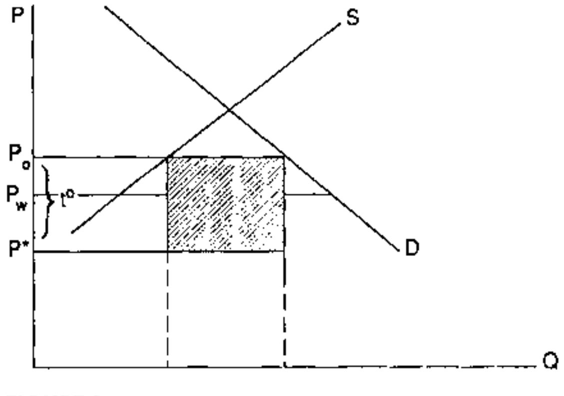

FIGURE 2 Tariffs in the large-country case.

There are cases where a tariff can result in net economic gains. Note that the government collects the entire cross-hatched area as tariff revenue. It, plus the producer gain, more than offsets the loss to consumers as a result of the tariff. Thus, tariffs result in a net economic or social welfare gain in the importing country.

An "optimal" tariff is one that maximizes social welfare (producer gain plus tariff revenue minus consumer loss). This is achieved when the duty-paid price is the same as the price at the intersection point of the demand curve D with the sum of S and the marginal outlay curve of the foreign excess supply curve. This type of tariff can lead to a welfare gain because the importer is exerting "monopsony" power against the exporter.

Often tariffs are variable in nature. For example, instead of the fixed tariff t^0 in Fig. 2, suppose the government in the importing country wanted to maintain the internal producer price at P_0 but supplies in the exporting country fluctuated because of weather. In response, the importer would adjust the tariff level (i.e., it would use a variable levy).

The above assumes that the exporter does not retaliate even though the exporter is harmed by the tariff (note earlier that export prices fell as a result of the tariff). The important situation which emerges with tariffs is that the amount which the importing country gains is less than what the exporting country loses. This is why from a global perspective, where both importers and exporters are taken into account, free trade is optimal.

C. Optimal-Revenue Tariffs

Governments do use tariffs to advertently collect revenue from imports. The tariff which maximizes government revenue is generally not one of those shown earlier. Conceptually this tariff is set so the government can exploit both exporters and domestic consumers. In Fig. 3 the excess supply curve is *ES*, while *ED* is the excess demand curve for the importer. Under free trade, the world price is P_w and Q_w is imported. The optimal tariff referred to earlier is t^0 (where the marginal outlay curve, MO, crosses the excess demand curve), which results in imports being reduced to Q^0. However, this is not the optimal revenue tariff. It is $P_1 - P_2$ per unit of import (determined by the intersection of MO and MR where the latter is the marginal revenue schedule to *ED*). The tariff revenue collected is P_1abP_2. Note that imports are Q^*, which are below those under the optimal tariff.

D. General Equilibrium Tariffs

The effects of tariffs can also be shown for more than one country (Fig. 4). The aggregate production possibility for agriculture and manufacturing is represented by X_1X_2. At relative prices (terms of trade) represented by P_1, the output of manufacturing is *M*, while *A* of agriculture is produced. This is under no trade. At free trade, the relative price is P_2. Output of agriculture increases to $\bar{A}$ but production of manufacturing decreases to $\bar{M}$. Welfare is improved under free trade (C_2 which indicates consumer welfare lies above C_1).

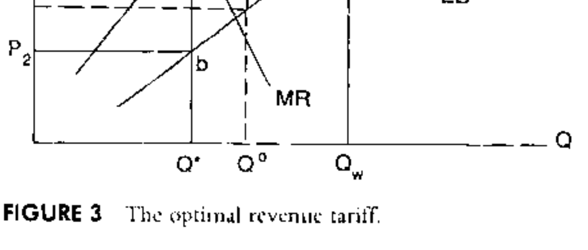

FIGURE 3 The optimal revenue tariff.

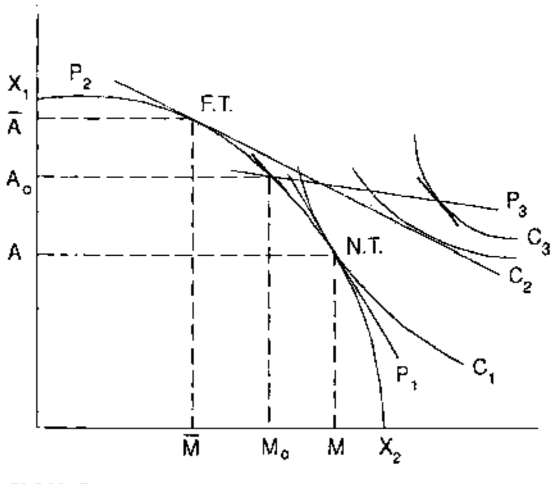

FIGURE 4 Tariffs in general equilibrium.

A tariff causes production to fall between the free-trade and no-trade points. For example, for a tariff which changes the terms of trade to P_3, agricultural output is A_0 and M_0 represents manufacturing output. This tariff is welfare improving (C_3 lies above C_2).

In all the cases where tariffs are welfare improving, the important assumption is that the trading partner does not retaliate. Under extreme retaliation, tariffs can be welfare reducing since, at the extreme, tariffs would become trade prohibitive.

E. Countervailing Duties

Border disputes often arise over accusations of unfair trade. One form is dumping where an exporter sells to an importer at a price below the cost of production or sells abroad at a lower price than it charges its domestic customers. For example, in Fig. 5, total supply in the exporting country is S_Q. The demand in the exporting country is D_d, while the demand in the importing country is D_f. Now, if the exporter sells quantity Q^* at a price P^* in the home market and Q^{**} at P^{**} abroad, export dumping occurs. The importer (whose demand is D_f) can retaliate with a countervailing duty (e.g., D^0). This will cause the exporter not to price discriminate, at which time the importer will remove the duty. The result will be free trade resulting in price P^0. Less is shipped abroad than before (Q^0 instead of Q^{**}) and more is consumed domestically.

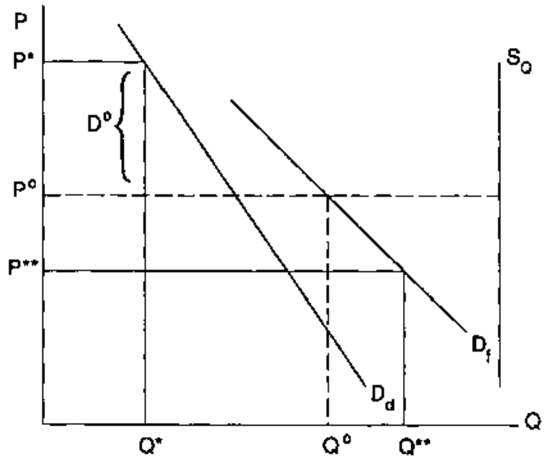

FIGURE 5 Export dumping and retaliation.

F. Effective Tariff Rates

A distinction is usually made between "nominal tariff" rates and "effective tariff" rates. The above discussion has focused on nominal tariffs since only tariffs on the final product are considered. Where inputs into production are traded and tariffs are also levied on the importation of these inputs, the tariff structure for the entire industry has to be considered. The rate of protection to the industry is called the "effective protective rate."

The nominal tariff rate can be misleading in cases where tariffs are imposed on related raw materials or intermediate products. As a result, the traditional nominal tariff rates may not give an accurate picture of the extent of protection afforded any given industry or the height of the average tariff of a country.

G. The Scientific Tariff

A scientific tariff structure includes noneconomic arguments for protection; however, it is difficult to reconcile the conflicting objectives of protection in a single scientific tariff structure. Tariffs are used to promote noneconomic objectives of various kinds through their influence on domestic production and consumption of certain products. Examples of the many tariffs classified as scientific include the following:

1. A tariff to promote national self-sufficiency and independence.
2. A tariff to promote diversification and industrialization or agriculturalization.
3. A tariff to promote a way of life.
4. A tariff to increase military preparedness.
5. A bargaining tariff.
6. A tariff to promote food security.

Each of these tariffs have associated costs and benefits. Consider, for example, a tariff to promote a way of life. This, along with other arguments, has been used to support high prices for farmers in the European Community (EC) and in Mexico. As Barkema noted,

> The Mexican government has a long tradition of safeguarding the interests of the nation's large number of small farmers. About a third of the Mexican population live in rural areas, and about a fourth are employed in production agriculture. The primary objective of Mexican farm policy is to boost incomes to small farmers, thereby minimizing rural unrest and slowing the pace of migration to Mexico City and other crowded urban areas. An important component of Mexican farm policy is restricting imports of low cost farm products from the United States and elsewhere. By blocking farm imports at the border, Mexican farm policy pushes up farm prices and incomes.

While farmers benefit from tariffs, there are some associated costs. One such cost is an increase in food prices paid by the urban people. These costs, in part, motivated Mexico's entry into the GATT and North American Free Trade Agreement (NAFTA) negotiations.

Some of the tariffs listed under the scientific tariff above actually fall into the earlier tariff categories. For example, a bargaining tariff could fit into the category of countervailing duties, since in essence an importing nation when it imposes a countervailing duty is retaliating or bargaining with an exporter to remove unfair trade practices.

Of the tariffs listed, the most popular one appears to be the tariff that promotes food security and food self-sufficiency. Strong arguments for food security have been made in view of world famine and food shortages during war time. As we will show in the empirical section, the problem with such an argument is that a policy put in place to achieve food security generally ends up resulting in excess production. For example, food security was an argument for introducing a high level of farm price supports in the European Economic Community. Over time, because of these high supports, the EC became a major exporter of food and found itself in a food overproduction situation, having to export at highly subsidized rates. In this example the EC achieved much more than any reasonable degree of food security or self-sufficiency. In other words, a food security, self-sufficiency policy ended up with some undesirable economic consequences. [*See* WORLD HUNGER AND FOOD SECURITY.]

II. How Important Are Tariffs?

A. United States and Mexico

For certain products and countries, tariffs represent a significant barrier to international trade. Recent U.S. agricultural export statistics are shown in Fig. 6. Japan is the largest importer, followed by the EC, Canada, and Mexico. For the 1990–1992 period, U.S. exports to Japan were roughly $8 billion. The United States has been in almost continual negotiation with each of these major trading partners in attempts to improve market access. In this section we consider the North American trade situation and, in the following section, the EC situation.

There have been attempts at trade liberalization through the Canadian and United States Trade Agreement (CUSTA) and with the proposed NAFTA. The latter seeks to remove the numerous barriers that restrict agricultural trade in North America. The primary players in the NAFTA accord have been the United States and Mexico since, under CUSTA, many farm trade issues between Canada and the United States were already addressed. A breakdown of U.S. farm trade with Canada and Mexico is shown in Table I. Fruits, juice, and vegetables comprise the largest component of U.S. exports to Canada, while livestock and products are the largest component of exports from Canada to the United States. U.S. exports to Canada are slightly greater than U.S. imports from that country. Grains, oilseeds, and products comprise the largest component of U.S. exports to Mexico, whereas fruits, juice, and vegetables are the largest component of U.S. imports from Mexico. The value of U.S. imports from Mexico roughly equals the value of U.S. exports to that country.

TABLE I
U.S. Farm Trade with Canada and Mexico in 1990

	To Canada		To Mexico	
U.S. exports	$1000	%	$1000	%
Livestock and products	802,216	19	662,068	26
Grains, oilseeds, and products	848,609	20	1,287,490	50
Fruits, juice, and vegetables	1,709,397	41	237,020	9
Other	837,193	20	367,038	14
Total	4,197,415	100	2,553,616	100
	From Canada		From Mexico	
U.S. imports	$1000	%	$1000	%
Livestock and products	1,491,822	47	466,199	18
Grains, oilseeds, and products	775,334	25	71,298	3
Fruits, juice, and vegetables	208,211	9	1,346,360	52
Other	605,018	19	726,851	28
Total	3,152,385	100	2,610,708	100

Reprinted with permission from A. Barkema (1992). North American Free Trade Agreement, what is at stake for U.S. agriculture? *Econ. Rev. Fed. Reserve Bank Kansas City*, 3rd Quarter, 7.

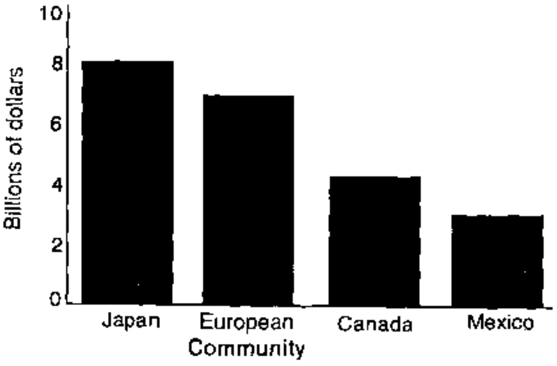

FIGURE 6 U.S. agricultural exports, 1990–1992 average. [A. Barkema (1992). "North american free trade agreement, what is the state for U.S. agriculture?" *Econ. Rev. Fed. Reserve Bank Kansas City*, 3rd Quarter, 6]

Mexico used an array of tariff and nontariff barriers to protect its many small farmers from foreign competition, while the United States restricted imports to protect the domestic horticultural industry and to ensure the safety of food imports from Mexico (Table II). Mexico restricted the imports of U.S. farm products with import license requirements and tariffs ranging up to 15% for grain and oilseed products and up to 20% for various meat, dairy, and horticultural products. The average tariff on U.S. farm exports to Mexico was in the neighborhood of 5% in 1992. Note that license requirements were also in place and acted to enforce import quotas. Even though tariffs have been reduced, license requirements remain and are a major restriction on many of the most important U.S. farm exports to Mexico. For example, import licenses for corn and wheat are not granted until the entire domestic crop is used. Also, import licenses for horticultural crops close the Mexican border to U.S. imports during the Mexican harvest season. A combination of license requirements with tariffs restricts imports of U.S. poultry and dairy products.

TABLE II

Major Restrictions on Farm Trade between Mexico and the United States, 1992

	Import restrictions imposed by	
Products	Mexico	United States
Livestock products	20% tariff on most pork products	Dairy and meat quotas
	10% tariff and license requirement on poultry products	Tariffs on many dairy, meat, and poultry products
	10–20% tariff and license requirement on most dairy products	1.2% tariff on live cattle
	Sanitary requirements	Sanitary requirements
Grains and oilseeds	0–20% tariff on most grains	Some small tariffs
	Seasonal 10% tariff on soybeans	
	Seasonal 15% tariff on sorghum	
	License requirements	
Horticultural products	10–20% tariff	Seasonal tariffs up to 25% on many fresh vegetables
	License requirements	35% tariff on dried onions, garlic, cantaloupe, melons
		Phytosanitary regulations

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In terms of U.S. trade barriers, tariffs are intertwined with stringent technical regulations on food imports which guard the quality and safety of the U.S. food supply. The average tariff facing Mexican farm exports to the United States is about 6%, which is slightly greater than the average tariff facing U.S. farm exports to Mexico. However, there is one important difference. Generally Mexican farm exports to the United States are subject to relatively few quantitative restrictions (i.e., quotas or import licensing schemes). The U.S. horticultural industry receives the highest protection, with an average 8% tariff on U.S. imports of horticultural products from Mexico. Seasonal tariffs reach as high as 35% and are assessed during the U.S. harvest season.

To highlight that tariffs are not the only major barrier to trade, quality, health, and sanitary standards also play a prominent role in regulating U.S. imports of horticultural and livestock products from Mexico. The United States, for example, regulates the use of farm chemicals on imported horticultural crops. It also maintains strict health and sanitary standards on livestock product imports, and imports of fresh citrus products are generally restricted to those grown in a few areas of Mexico that have been certified "fly free."

It is possible to put together numbers on tariff and nontariff barriers between Canada and the United States and to show how these have changed due to CUSTA. Likewise, it is possible to tabulate the tariff and nontariff barriers present in agricultural trade between the EC and the United States. As is the case between Mexico and the United States, for certain products there are significant tariff barriers to trade as well as significant nontariff barriers such as quotas and licensing schemes.

B. The United States and the EC

Barriers to agricultural trade between the United States and the EC have been at the heart of the problem to achieve any resolution under the GATT. Even though there have been several years of trade negotiations under the auspices of GATT, there had been no resolution as of January 1, 1993. The United States and the EC are major competitors in international agricultural markets; they are also major trading partners. The EC accounts for roughly one fourth of U.S. agriculture exports. A summary of program supports for agriculture in both the United States and the EC by major commodities is presented in Table III. Note that tariffs play a role as an instrument for supporting agriculture. For example in the United States, tariffs play a role in supporting the income of dairy farmers and of livestock producers. In the EC, tariffs are important for dairy, grains, livestock, and sugar. The term "variable import levies" appears in Table III. This is simply a variable tariff which moves up and down depending on market supply and demand conditions.

The EC uses variable levies on imports on U.S. beef, veal, and live animals. The actual levy has ranged from 0 to 114% of the basic levy, depending on the relation of the EC internal prices to what is called "guide prices."

Concerning dairy products in the EC, butter and skim milk are purchased at fixed intervention prices. A threshold (minimum import) price for milk and dairy products is enforced by variable levies that are equal to the difference between the threshold and world prices. Table IV is presented to show the complexity of agricultural programs, including border protection measures such as tariffs for one sector—the

TABLE III

Summary of Program Supports for Agriculture, United States and EC

Commodity	United States	EC
Dairy	Price supports maintained by tariffs, quotas, and government purchases.	Price supports maintained by intervention purchases.
Grains	Deficiency payments.	Variable import levies. Export refunds. Production quotas. Consumption subsidies.
	PIK entitlements.	Price supports maintained by intervention purchases.
	CCC inventory operations and commodity loans.	Variable levy. Export refunds.
Livestock	Beef: tariff, quota (countercyclical), and purchases (4/86–9/87).	Beef price supports maintained by intervention purchases.
	Other: general (research and development, inspection).	Variable import levies and export refunds on all products.
Oilseeds	CCC inventory operations and commodity loans.	Deficiency payments.
Sugar	Price supports.	Price supports maintained by intervention purchases.
	Import quotas.	Variable import levies. Export refunds. Production quotas.

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grain sector for the United States and the EC. Note that the United States does not have any border protection measures for grains with reference to the EC; however, the EC uses a threshold (minimum import prices) which is enforced by variable levies which are adjusted daily to equal the difference between threshold and world prices. This is also applied to the grain content of processed products. Table IV also shows the price support and the production control measures, and the stock and surplus disposal measures used in both countries. The EC has high price supports and its policy does not constrain agricultural production, although reforms introduced in 1992 sought to change this. On the other hand, in order for a U.S. producer to participate in the farm program, acreage set asides are required.

Concerning our earlier discussion, note that to dispose of surplus stocks the EC uses export subsidies which are set weekly as the difference between EC and world price changes. For commodities such as wheat, the EC has moved from a major importer to a major exporter, largely through the maintenance of high price supports using variable import levies. This has allowed EC farmers to increase production significantly, thus the EC has become one of the largest wheat exporters in the world. [*See* CROP SUBSIDIES.]

III. Case Studies

There is some evidence available which suggests that certain tariffs discussed theoretically have been used.

A. EC Variable Levies

A major study by Carter and Schmitz tested whether the EC was pursuing an optimal tariff strategy (modeled previously in Fig. 2), with its introduction of the variable levy system. It found that this was an optimal tariff strategy, and there were significant economic gains from such a policy. The results are shown in Table V. However, these results apply not only to the EC, but to China and the C.I.S., which are major wheat importers as well. As theory suggests, there is a loss in consumer welfare from the tariff because of higher prices; however, this is more than offset by the gain in producer revenue and by the gain in import tariff revenue. Note (from Table V) that the gain in tariff revenue is larger than the gain in producer revenue. The net gain from pursuing this strategy was roughly $3.8 billion.

As pointed out earlier, tariffs maintained for a long period of time encourage overproduction. This is essentially what happened in the European Common Market (ECM) with respect to wheat production. When the Common Agricultural Policy (CAP) was introduced (the early 1960s), the EC was a major importer; by the early 1990s the EC was a major exporter along with the United States and Canada. The EC leads both Argentina and Australia as a major wheat exporter. As a result of these dynamics, the optimal tariff strategy by the EC is no longer valid since the EC is now a net exporter.

TABLE IV

Grain Program Supports, United States and EC

Price support measures	Production control measures	Stock and surplus disposal measures	Border protection measures
United States			
Price supports maintained through nonrecourse loans to producers at established loan rates using the crop as collateral. If the market price falls below the loan rate, then producers may keep the loan and forfeit the crop.	Production is limited through voluntary producer participation in acreage reduction programs (participation is required for loan and deficiency payment eligibility). Voluntary paid land diversion programs have periodically been offered to increase acreage set-asides.	Commodity certificates for public stocks have been issued as partial payment for deficiency payments, the conservation reserve, the export enhancement program, PL 480, and wheat donations under Section 416.	None.
Income supports maintained through deficiency (direct) payments to producers. The payment rate is the difference between a target price and the higher of either the loan rate or the market price. Commodity certificates redeemable for government stocks have been used as part of the deficiency payments.	Participating producers may reduce permitted planted acres up to 50% and still receive 92% of their deficiency payments.	Farmer-owned reserve (FOR) maintained for longer term (3 – 5 years) storage of wheat and feed grains.	
EC			
The EC is obligated to purchase all grain offered that meets minimum standards at intervention prices that are fixed annually. A co-responsibility levy (production tax) reduces effective producer receipts by 3% on marketed grain. For durum wheat, direct payments are made to producers in low-yield areas. Wheat and rye meeting higher standards receive up to 7% higher prices than for the minimum qualities.	Up to 45 million acres of cropland will (by 1990) be placed in a conservation reserve for 10 years. A production threshold is set and, if a 3-year average of actual production exceeds the threshold (adjusted for imports of nongrain feeds), price support increases are supposed to be adjusted downward. Annual price setting remains at the discretion of the EC Council of Agricultural Ministers, however.	National intervention agencies hold stocks purchased at the intervention level. Surpluses are disposed of with export subsidies that are set weekly as the difference between EC and world price changes.	Threshold (minimum import) prices enforced by variable levies that are adjusted daily to equal the difference between threshold and world prices. This is also applied to the grain content of processed products.

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TABLE V

Welfare Gains to Wheat-Importing Nations with the Imposition of the Optimal Import Tariff

Welfare effect	Net gain $U.S. millions
1. Loss in consumers' surplus	−9439
2. Gain in producers' surplus	5971
3. Import tariff revenue	7202
4. Net gain (3 + 2 − 1)	3734

Source. Calculated. C. Carter and A. Schmitz (1979). Import tariffs and price formation in the world wheat market." *Am. J. Agricult. Econ.* **61**, 520.

B. Japanese Beef Imports

Considerable controversy has surrounded the Japanese beef policy, which has been highly restrictive in allowing imports into the country from the United States and elsewhere. For many years, the Japanese restricted beef imports through the use of an import quota. Prior to April 1, 1990, the primary mechanism used to protect the domestic beef industry was "on the quantity of beef" which could be imported; but, on April 1, 1990, the quota was replaced by a 70% tariff. What was this tariff to achieve?

First, the tariff supports beef producers' incomes in Japan. Second, Japanese beef prices are much higher than those in many trading nations. Third, the tariff allows the Japanese government to collect substantial income on imports via tariff revenues. Wahl, Hayes, and Schmitz test the extent to which the beef tariff is optimal from a society standpoint, or whether it is used to maximize the revenue collected by the Japanese government from the tariff. Interestingly, a tariff in the neighborhood of 70% was found to maximize government revenue (Fig. 4), while one of 50% was closer to maximizing social welfare (Fig. 3). Thus, the Japanese proposal to lower tariffs to 50% implies that they are moving toward an optimal social welfare position. Note that the optimal revenue tariff is higher than the optimal welfare tariff, as suggested by theory.

In terms of the Japanese, the government's behavior is consistent with the hypothesis that the Japanese government acts as a self-interested middleman. As the theory shows, an optimal revenue tariff is akin to a government middleman, which essentially exerts monopsony power on sellers and monopoly power on buyers. In terms of the Japanese beef tariffs, Fig. 7 shows the tariff revenue as a function of tariff levels. As the graph indicates, the tariff revenue is roughly at a maximum for tariffs that range between 70% and 100%.

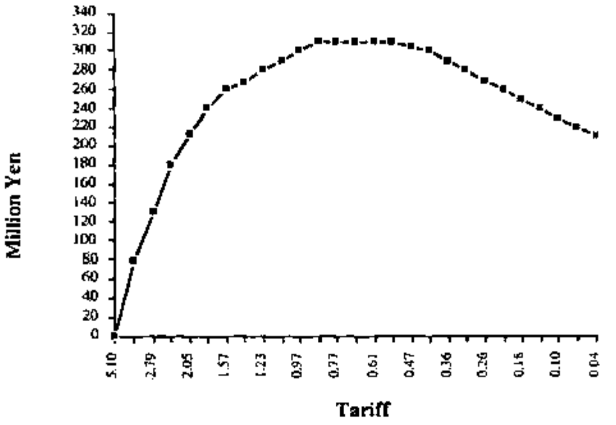

FIGURE 7 Japan: Beef import tariff revenues (1993). [Wahl, T., Hayes, D., and Schmitz, A. (1992). "The Japanese beef policy: Political preference function" in Agriculture and Trade in the Pacific Rim: Toward the Twenty-First Century" (Coyle, W. T., Hayes, D., and Yamauchi, H., eds.), p. 303. Westview Press, Boulder/San Francisco.]

C. Canada–United States Potash Dispute

The theory of a countervailing duty and its impact, as discussed previously, has been applied to several agricultural cases, including the potash dispute between Canada and the United States. Potash is a major fertilizer component used in U.S. agriculture, and Canada is a major supplier. On 10 February 1987, two American firms (Lundberg Industries of Dallas, TX, and New Mexico Potash Corp. of Memphis, TN) filed a lawsuit against several Canadian producers for dumping potash in the United States at prices which were alleged to be 43% below the cost of production. In 1987 these two firms accounted for less than 15% of the potash consumed in the United States. The suit was filed through the U.S. Department of Commerce and the U.S. International Trade Commission. The International Trade Commission agreed on 3 April 1987 that there was unfair price discrimination and on 21 August 1987 the United States announced preliminary duties on Canadian potash. Canada did respond by raising prices by over 30% and adjusted production accordingly. In response, the United States removed duties on potash entering the U.S. market. What were the effects?

The users of potash in the United States stood to lose because potash prices were raised as a result of the court action brought by American potash producers. On the other hand, potash producers stood to gain from their legal pursuit. Ironically, the U.S. farmers in this case lost much more from the legal transaction than what the U.S. potash producers gained. This was because the U.S. producers essentially were receiving a subsidy from the Canadian government on potash being produced in Canada and shipped into the U.S. market. U.S. potash producers gained roughly $13 million, Canadian potash producers gained roughly $108 million, and U.S. farmers lost roughly $70 million (Table VI). The net effect from the countervailing duty was positive—both for Canada and the entire North American market (approximately $51 million).

D. Tariffs and Quotas

As the earlier tables suggest, quotas are used extensively to restrict imports. In the United States, for example, these are common for sugar and peanuts. In Canada, they are commonplace for supply-managed products such as eggs and poultry. Quotas differ from tariffs in at least one important respect. Under a tariff, financial benefits flow to the government in the form of tariff revenues but, under import quotas, the financial benefits more often flow to exporters in the form of higher prices. There are exceptions, however. In the Japanese beef case, when quotas were in place prior to their replacement with tariffs, the Japanese collected the quota rents. However, in the U.S. sugar case, the quota rent actually is retained by exporters of sugar to the United States. In Canada, the importer quota rents are received by private importers such as retailers and food processors.

There has been a general move to replace quotas with tariffs, as has been the case for Japanese beef. Table VII shows Canadian implicit tariffs (i.e., the equivalent tariff that would raise the border price to the internal quota price) on chicken imports. These cases are roughly equivalent to the protection afforded by existing sugar quotas. At times the implicit tariff exceeds 50%. If GATT is resolved in line with current proposals, not only will "tariffication" of quotas proceed, but also tariffs will be lowered over time.

TABLE VI

Effects of U.S. Potash Countervailing Duties

U.S. potash producers	+$ 12.9 million
Canadian potash producers	+$108.4 million
U.S. farmers	−$ 70.4 million
Net effect	+$ 50.9 million

Source. Picketts, V. J., Schmitz, A., and Schmitz, T. G. (1991). Rent seeking: The potash dispute between Canada and the United States. *Am. J. Agricult. Econ.* **73**, (2), 255–265.

TABLE VII

Canada: Chicken Prices and Implicit Tariffs in the 1980s

Year	Canadian price[a]	U.S. price[b] C$/kg	Transport cost[c]	Implicit tariff (%)
1980	1.662	1.207	0.094	29.9
1981	2.007	1.225	0.096	56.0
1982	1.955	1.193	0.098	55.6
1983	2.092	1.340	0.098	48.8
1984	2.286	1.594	0.104	36.9
1985	2.032	1.534	0.110	25.3
1986	2.182	1.744	0.111	18.8
1987	2.082	1.390	0.106	42.1
1988	2.115	1.527	0.098	32.1
1989	2.478	1.535	0.094	55.3

Source. Moschine, G., and Meilke, K. D. (1991). Tariffication with supply management: The case of the U.S.–Canada chicken trade. *Can. J. Agricult. Econ.* **39**, 61.

[a] Wholesale price in Ontario. *Source*. Agriculture Canada.

[b] U.S. 12-city wholesale price. *Source*. USDA (expressed in Canadian currency).

[c] *Source*. see text.

IV. Conclusions

In conclusion, we present some empirical evidence on the effects of trade liberalization in agriculture. These results are for removal of not only tariff barriers but also nontariff barriers, including quotas. Thus, the results overstate the economic impacts of removing tariff barriers. Numerous large-scale models have been developed to estimate the impact of free trade, and these models were developed largely in response to the GATT negotiations.

A. The Organization for Economic and Cooperation Development (OECD)

According to the OECD, the world market effects of trade liberalization by commodity are as follows.

Wheat The price rises 18% and production increases 0.5%. World trade declines 1.5%.

Rice The price rises 21% and production increases 1%. World trade increases 37%.

Feed grains The price rises 11% and production increases 2%. World trade declines 5%.

Bovine and ovine meat The price rises 17% and production increases 3%. World trade jumps 35%.

Dairy The price rises 31% and production increases 2%. World trade goes up to 13%.
Other animal products The prices are unchanged and production rises 1%. World trade increases 17%.
Protein feeds The price rises 13% and production increases 2%. World trade rises 5%.

B. The Tyers and Anderson Model (TA)

According to TA, the world price and trade effects of industrial market economy liberalization only on agricultural markets are:

Wheat The world price rises 2% and trade declines 1%.
Coarse grains The world price increases 1% while the trade rises 19%.
Rice The price rises 5% and trade increases 32%.
Beef The price increases 16% while the traded amount rises 195%.
Pork and poultry The price rises 2% and trade increases 18%.
Dairy The price jumps 27% and trade increases 95%.
Sugar The price increases 5% and trade increases 2%.

C. Food and Agricultural Policy Research Institute (FAPRI)

Generally the FAPRI results are much higher with respect to trade liberalization than the results from the other studies. Significant changes are expected to occur within the EC itself when it implements a 15% set-aside requirement and lowers intervention prices. Under this CAP reform alone, FAPRI estimates that wheat prices will increase somewhere in the neighborhood of 18%, corn 11%, barley 8%, soybeans 12%, and soybean oil 23%. However, only minor changes will occur in soybean meal, beef, pork, poultry, and dairy.

The impact of trade liberalization is significant, especially with respect to world prices for agricultural commodities. Some commodities are affected more than others; this is clearly the result of the level of protection that currently is afforded various commodities. Estimates of the effects of liberalizing trade differ. This is not surprising, given the complexity of international markets and the shifting dynamics of their interaction. But almost all of the estimates conclude that eliminating all tariffs and other trade barriers would improve the world's economic condition. However, whether producers would gain from freer trade depends on the type of product produced and the level of government support through such measures as deficiency programs. In the United States, some farm groups would lose from free trade (if all farm support measures were removed) because the positive price increase effect from liberalized trade would be less than the negative effect caused by the reduction in various forms of nontariff government support.

Acknowledgment

The author thanks Dr. Kirby Moulton and Dr. Jerry Seibert for their comments on earlier drafts.

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Tea

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Glossary

Harvesting index Ratio of economic yield and total biological yield. The harvesting index of tea plants varies according to the location, it generally ranges between 7.5 and 14.7%, compared with 30% or more for other crops

Pluckable shoot Terminal bud of the tea shoot that develops to attain the pluckable maturity; plucking standard of the shoot is determined according to the different kinds and grades of tea; shoots with one bud and two to three leaves are generally plucked and ready for manufacture

Tea polyphenol One of the important components constituting the tea quality; it is a mixture of polyhydroxy phenolic compounds existing in tea plants; main components include catechins (flavanols), flavones, flavonols, anthocyanins, and phenolic acids

Tea plant (*Camellia sinensis*) originated in the southwest part of China, and has been cultivated for more than 3000 years. Now, tea plants are cultivated in 54 countries around the world. Nearly one-half of the population in the world consumes tea. Tea, coffee, and cocoa are the three most popular beverages in the world.

I. Development of the Tea Industry

The discovery and utilization of tea originated during the "Shen-Nong" era of ancient China, around 5000 to 6000 years ago. Originally, tea was used as a medicine for various ills; it can be traced back to the "Xi-Han" era (200 B.C.). Tea production has been developed rapidly since the Tang dynasty (618–907 A.D.), and has been accepted as a beverage; however, tea has achieved popularity in other parts of the world only since the middle of the 17th century. Commercial cultivation of tea gradually expanded to Indonesia, India, and Sri Lanka until the middle of the 19th century. The tea cultivation history in Africa is relatively short. The first record of cultivation in Africa is in 1850; however, the tea industry was developed until the middle of the 20th century. Now, tea plants are distributed worldwide ranging from 42° N to 33° S. It is now grown commercially in tropical and subtropical regions of Asia, Africa, and South America, and also in limited areas in North America and Australia. In 1990, the tea-growing area in the world amounted 2.45 million ha, total output amounted 2.51 million tons, and green tea comprised about 21% of the total. The average yield per unit area in the world is around 1004 kg/ha. Eight major tea-producing countries (India, China, Sri Lanka, Kenya, Turkey, Indonesia, formerly Soviet Union, and Japan) accounted for 86% of the world production. Virtually all tea produced in Japan and about 60% of that produced in China is green tea. India is the largest tea producer; nearly all of which is black tea. The world total exports amounted 1.125 million ton in 1990, and is about 40% of total tea production. The exported tea from Sri Lanka has surpassed that of India since 1990, and is the greatest in the world (Table I).

II. Agrobotanical Characteristics

Although the tea plant is an ancient plant with a long history, the confusion and modification in nomencla-

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TABLE I
Tea Production in the Major Tea-Producing Countries

	Tea production (× 10,000 t)					
Country	1940	1950	1960	1970	1980	1990
India	21.16	27.85	32.11	41.85	56.96	71.47
China[a]	—	6.22	13.58	13.60	30.87	51.50
Sri Lanka	10.77	13.90	19.72	21.22	19.14	23.41
Kenya	0.49	0.68	1.38	4.11	8.99	19.70
Indonesia	8.34	3.54	6.78	4.40	9.97	15.04
Turkey	—	0.02	0.59	3.34	9.59	13.12
USSR	1.13	—	3.77	6.68	12.98	11.00
Japan	5.82	4.18	7.76	9.12	10.23	8.99

[a] Taiwan is not included.

ture have continued for almost two centuries. As early as 1753, Linnaeus described the tea plant as *Thea sinensis*, and it was modified to *Camellia sinensis* in August of same year. Since then, the genus name of *Thea* and *Camellia* has had a checkered history. In the second edition of *Species Plantarum*, Linnaeus abandoned the former name and described the two species separately: *Thea bohea* and *T. viridis*. Watt in India named *Camellia thea* in 1907; Cohen-Stuart in Indonesia used a new name of *Camellia theifera*. In 1950, a famous Chinese botanist, Qian Chongshu, nomenclatured *Camellia sinensis*. Sealy in the U.K. (1958) also gave the same name and included two varieties: var. *sinensis* (small-leaf variety) and var. *assamica* (large-leaf variety). Since that, despite some papers contributing to the botanical name of tea plant, uniformity has been achieved.

Botanically, tea belongs to the order Theales, family Theaceae, genus *Camellia*. All varieties and cultivars of tea belong to a single species, *Camellia sinensis*. Tea plant is a perennial evergreen; the aerial portion of tea plant is grown as tree, semi-tree, and shrub depending on the influence of the external environment. The China variety (var. *sinensis*) tea plant usually grows into a shrub about 1–2 m high, characterized by more or less virgate stems. Leaves are small, hard, dark-green in color with a dull surface. The *Assam* variety (var. *assamica*) is described as a erect tree with many branches, 8–12 m high. Leaves are 15–20 cm long, light-green in color, with glossy surface.

The fresh shoots are the economic harvest of tea plant. The phyllotaxy of leaves on the shoot is alternate. The leaf pose on the stem includes erect, semi-erect, horizontal, and drooping according to the variety. Leaves are leathery in texture, with silvery or light-yellow colored hairs on the undersurface of tender leaves. There are 7–15 pairs of veins on the leaf. The lateral veins curve upward and connect with the upper veins, forming a close transporting network, which is characteristic of the leaves of tea plants. Leaves are serrated at the margin. The first several new leaves at the flushing period of the tea shoot usually have a characteristic small size, being thick and brittle with a blunt apex; the petiole is wider and flat, and called fish-leaf or in Indian terminology the *Janam*. Its position on the shoot is of the very greatest importance when considering standards of plucking. The tea manufactured with the fish-leaf are of low quality. Sometimes the leaf primodium differentiates from the vegetative bud of tea plant ceasing growth prematurely instead of developing into the normal leaf. It is termed the dormant bud or in Indian terminology the *Banjhi*. Normal tea shoots show the distinct periodicity of growth, i.e., after the development of several normal leaves, the *Banjhi* bud forms, thus completing a full periodic shoot growth rhythm.

Tea flowers are bisexual with a slight fragrance and are white in color. Their diameter is 20–55 mm. The morphology of the flower is one of the important indexes in the classification of the tea plant. The fruit of the tea plant is green in color, three-celled, thick-walled, and shinny at first but then duller and slightly rough later. Tea seed is brown in color, thin-shelled, about 1 cm in diameter, and semiglobose in shape.

III. Nutrition and Cultivation

Tea plants can be grown over a considerable range of conditions from temperate climates to hot, humid subtropics and tropics. However, the optimum mean daily ambient temperature for tea growth is ranges between 20 and 30°C. When the mean ambient temperature is higher than 30°C, the growth of the tea plant is retarded. The tolerance of tea plant to the minimum temperature varies with the varieties, it generally ranges between −3 and −15°C. Tea plants require not only certain amounts of rainfall, 1000–1700 mm annually, but also rainfall that is well-distributed during the whole year, especially the growing season.

Tea plants are not overcritical to soil. The range of soil types on which tea is grown in the major tea-producing countries in the world is remarkably wide. Tea plants are very sensitive to the acidity of soil. They cannot survive in alkaline soils. The optimum pH of soil for tea growing ranges between 4.5 and 6.5. Table II shows the physiochemical parameters of a high-yielding tea garden in China. [*See* Soil, Acid.]

The tea output per unit area is proportional to the coverage in tea garden. For the purpose of obtaining the maximum productivity within short period, a density of more than 12,000–20,000 bushes per hectare in large-leaf varieties and 45,000–60,000 bushes (20,000 bushes × 3 rows) in small- to medium-leaf varieties is recommended. The economic age of the tea plant is generally around 40 years. It is recommended to pull out and replant the new clones when the tea plants reach this age. However, such techniques as collar-pruning and heavy-pruning of old bushes are adopted in China, Sri Lanka, and other countries in order to obtain the benefits during the early period.

The principle of fertilization is to compensate the nutrients removed by the crop and eluted by the rainfall in a timely manner. Ordinarily, the schedule of fertilization is determined according to the nutritional status in the tea soil, the yield level in the previous pruning cycle, and the yield predicted by agrometeorological conditions. On this basis, the level of nitrogen application is controlled around 240–300 kg per hectare and half amounts of potassium are added; the level of phosphorus is fixed at amounts of 60–90 kg P_2O_5 per hectare and applied every 2 years. [*See* Fertilizer Management Systems.]

The requirements for microelements by tea plant are few. It is not important in most of the tea-producing areas; however, deficiencies were found in some particular instances. For example, in areas of Malawi and Japan are copper deficiencies, part of the soil in Sri Lanka and east African countries are zinc deficient, part of the areas in Indonesia, east Africa, and Zaire are magnesium deficient. So, the application of microelement fertilizer produced significant effects in some instances.

The direct effect of shading is to modify the situation of light, airflow, temperature, and humidity as well as to decrease the physical damage of solar radiation; the indirect effect is to minimize the excessive evaporation of water from leaves. Besides, the fallen leaves of the shading tree increase the source of organic matter; however, shading increases the incidence of tea blister blight (*Exobasidium vexans*) due to the shade tree minimizing the solar radiation. So, the benefit and risk analysis of shading are a disputed issue, possibly because of the wide geographical distribution and various climate conditions. It is regarded that shading is necessary in tea areas with a maximum temperature higher than 35°C and relative humidity lower than 40%.

Although the total rainfall in a year may be adequate for the production of green leaves in most tea areas in the world, the distribution of this rainfall month

TABLE II
Main Physiochemical Parameters of High-Yielding Tea Garden in China

Physical characteristics		Chemical characteristics	
Effective soil horizon > 80 cm		Acidity	Water extracts pH 4.0–5.5
			Salt extracts pH 3.5–5.0
Ploughing horizon > 20 cm		Exchangeable Al	Al^{3+} 1–4 mg/100 g
Soil texture	Sandy-loam to heavy loam	Exchangeable Ca	Ca^{2+} < 4.0 mg/100 g (CaO < 0.1%)
Bulk density (loam)	Surface 1.0–1.2 g/cm^3	Degree of base saturation (loam)	Ca^{2+} < 50%
	Subsoil 1.2–1.45 g/cm^3		Mg^{2+} around 10%
			K^+ > 5%
Porosity	Surface 50–60%	Tillage horizon	Organic Matter > 1.5%
	Subsoil 45–50%		Total N > 0.1%
Ratio of three phases	Surface Solid: 50		Available N > 1.00 mg/kg
	Liquid: 20		Quick acting P > 10 mg/kg
	Gas: 30		(dilute HCl Extracts)
	Subsoil Solid: 55		Quick-acting K > 80 mg/kg
	Liquid: 30		(NH_4Ac extracts)
	Gas: 15		
Water-permeable coefficient > 10^{-3} cm/sec			

by month is often inadequate. This can be regulated by irrigation. Irrigation not only supplements the water supply to tea bush, but also modifies both the atmospheric and the soil environment. It was also proved that the shoots from irrigated gardens had higher polyphenol content. The optimum time for irrigation can only be decided according to the local situation. However, it is believed that irrigation is most beneficial when it carried out early in the dry season before the water deficiency is severe.

Pruning is a "necessary evil" to the tea plant. The objects of pruning are to maintain the plant permanently in the younger phase, to stimulate the growth of shoots, and to build an rational height of frame. In mature tea gardens, light-pruning and heavy-pruning should be done alternately. The best time for pruning is during a dormant period, because this is the time that the carbohydrates reserves within the tea plant are at a higher level. Pruning during drought season is not suitable. The rational for the plucking system is based on the fact that certain amounts of regrowth leaves remain on the plucking table, thus guaranteeing to supply enough carbohydrates to the tea shoots. Generally, the terminal bud is removed together with one to three leaves for manufacture. The interval of the plucking cycle on the tea plant mainly depends on the growth rate of the plant, generally 5–14 days. In most areas of the former USSR and Japan, plucking has been fully mechanized; however, most of the world's tea is plucked by hand.

Tea plant is a C3 plant with high photorespiration; the utilization ratio of the tea plant of solar radiation energy is far lower than that of other crops. According to a study in India, only 7% of the photosynthetic products are used in the growth of the tea shoot, 9% in the formation of frame branches, and 84% is exhausted during respiration and other metabolic actions. How to improve the harvesting index via the breeding route or through cultivation is a problem to be solved in the future.

IV. Kinds of Tea and Manufacture

The fresh leaves plucked from the tea plant are manufactured into various kinds of tea including black tea, green tea, Oolong tea, scented tea, etc., by means of different manufacturing methods. Fresh leaves treated with high temperature (de-enzyming or steaming) at the beginning of manufacture, to deactivate the polyphenol oxidase localized within the cells of leaves and to stop the fermentation, and to maintain the original green color, are termed unfermented tea (green tea). On the other hand, when the process begins with dehydration and leaves are not treated with high temperature, the tea polyphenols are oxidized completely by the enzyme, and produce fermented tea (black tea). When the enzymes in the tea leaves are not completely deactivated and the tea polyphenols are not oxidized fully, these products are the intermediate of black tea and green tea, termed semi-fermented tea (Oolong tea).

Black tea is the major kind of tea consumed in the world. The key process in the manufacture of black tea is fermentation. Congou black tea is manufactured by the most traditional processes including withering, rolling, fermentation, and drying. For the convenience of brewing, the tea cutter was developed first in India, and the rolling process was changed to a rolling and wringing processes; thus, the broken black tea product was produced. This kind of manufacture makes more water-extracts with same quantity of tea, thus improving the efficiency of the raw material. Subsequently some alternative manufacturing machines and methods were developed successively in India, East African countries, and China, include the Rotovane process, CTC process (crushing, tearing, curling), LTP process (Lauric tea processor). The production of CTC black tea was increased rapidly in the past 10 years.

The production of green tea is mainly concentrated in China and Japan, with a small-scale production in the former USSR, India, Indonesia, and Turkey. The basic manufacturing processes of green tea include de-enzyming, rolling, and drying. The de-enzyming process comprises pan-de-enzyming and steam-de-enzyming. The steamed green tea is the major tea product consumed in Japan. Due to the different terminal drying process, it can be classified into roasted and baked green tea. The roasted green tea is the major tea consumed in China and the African countries. The baked green tea is the raw material of scented tea. The propensity of the tea adsorbing flavors is used in the manufacture of scented tea. The baked green tea is mixed with dried fresh flowers to impact fragrance and aroma. The most popular flowers used in the scented tea are Jasmine, Michelia, Zhulan, Dae-dae (*Citrus aurantaium* var. *amara*), osmanthus, and rose. Oolong tea is a kind of semi-fermented tea. Its basic manufacturing process includes Shai-Qing (sunlight withering), Zuo-Qing (light rolling), de-enzyming, rolling, and drying. Not only the special tea variety and strict plucking standard are necessary, but also the elaborating manufacturing technique is required.

The plucking requirement for Oolong tea is different from that of other kinds of tea. It is recommended that shoots with three to four leaves be plucked as the raw material when the *banjhi* is formed on the terminal of shoot. Due to the distinct characteristic of various tea varieties and degree of fermentation process, different styles of Oolong tea are produced, such as "puochong" (light fermentation), Tie-Quan-Yin, and Shui-Xian (heavy fermentation).

Black–black tea is mainly produced in China and also on a limited scale in the former USSR. The manufacturing processes include de-enzyming, primary rolling, Ou-Dui (treatment of high temperature and humidity), secondary rolling, and drying. The fresh leaves used in the manufacture of black–black tea are rather coarse. Ou-Dui process is the special process in the manufacture of black–black tea and the key process in determining the quality of black–black tea. The products include Hei-Mao-Cha and Pu-Er. It is consumed in the minority nationality region of China, southeast Asian countries, Hong Kong, and Mongolia, and the former USSR.

Besides the above mentioned kinds of tea, there are many kinds of remanufactured tea made using the above made tea as the raw material, such as instant tea, brick-tea, fruit-flavored tea, and health-protecting tea (mixture of tea and Chinese traditional medicine).

V. Consumption and Customs

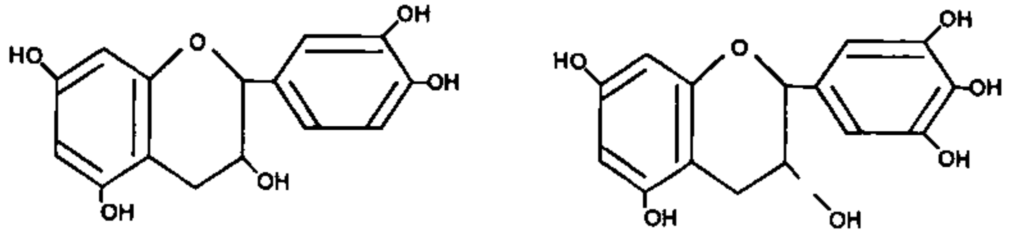
There are 125 countries and regions in the world that import tea. The imported amount by the former USSR in 1990 was 231,000 tons; this was the first time it surpassed the imports of U.K. and occupies the first place in the world. The United Kingdom was the largest tea importing country for a historical period. The imports amounted 141,900 tons in 1990, and occupied the second place. Imports of tea are listed successively in the following order: Pakistan, United States, Egypt, Iran, Iraq, and Poland. Ireland has the highest average annual consumption of tea per capita, according to statistics from 1986–1988, (3.07 kg/year), followed by Iraq (2.95 kg), Qatar (2.91 kg), the U.K. (2.84 kg), and Turkey (2.73 kg). The following characteristics can be summarized about world tea consumption during recent years: (1) the consumption of the largest tea importing country (U.K.) historically showed a decreasing tendency. (2) The internal consumption in the major tea-producing countries (India and China) increased rapidly. (3) The proportion of imports from the former USSR and eastern European countries were increased from 8.7% in 1980 to 24.4% in 1990; those of Asian and African countries were increased from 35.5% in 1980 increased to 43.7% in 1990. On the other hand, the imports of western European countries were decreased from 25.0% in 1980 to 21.7% in 1990. (4) The proportion of CTC black tea in the total world black tea trade increased significantly from 39% in 1980 to 47% in 1990. The proportion of tea bags and instant tea in the total tea trade increased.

The custom of tea drinking in China and Japan mainly adopts the brewing form, and in India, Sri Lanka, and European countries mainly adopts the cooking style. People from Asian and northern African countries prefer the green tea, and the black tea is the type most consumed by most parts of the world. Perfumed tea is popular in south American countries and mint green tea is popular in northwest African countries as well as buttered tea, salted tea, and Rei-tea in the border area of China. Instant tea, iced tea, liquid tea, and various tea bags which are simple and fast were developed with the changing life styles. Additionally, tea drinking with tea as the raw material was developed popularity in the markets of China, India, and Indonesia.

VI. Tea Biochemistry

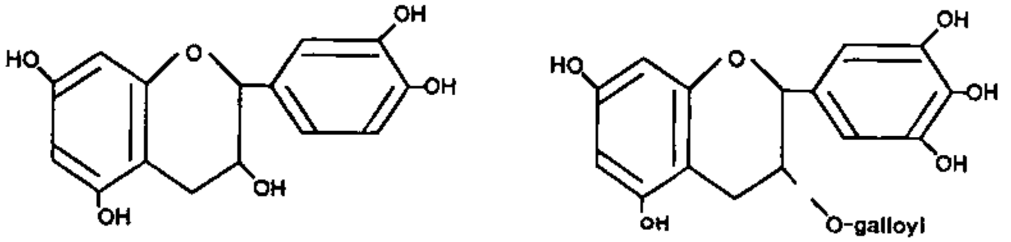
The quality of various kinds of tea is based on the contents and constitutions of various chemical components. Twenty-eight elements were discovered in tea plants. Tea contains more potash, manganese, fluorine, aluminum, and selenium than other plants. Tea is also rich in vitamins, especially vitamin C. It was reported that the content of vitamin C in 100 g green tea is as high as 100 mg. However, 90% of the vitamin C contained in tea fresh leaves is destroyed during the fermentation stages of black tea manufacture. The content of vitamin B group in green tea and black tea is around 10 mg per 100 g made tea. They are water soluble and hence 90–100% is extracted into the infusion during brewing. Vitamin E is exists mainly in the lipid fraction of made tea, and the content is around 14–80 mg per 100 g made tea.

Twenty-five amino acids are reportedly contained in made tea. The total content in tea shoots is as high as 2–4%. Among those, theanine is the highest and represents more than 50% of the total amino acids. It plays a special role not only in the nitrogen metabolism of the tea plant, but also in determining the taste and quality of tea infusion.



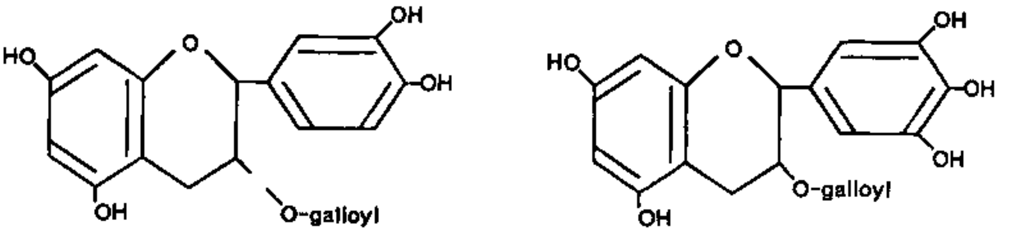
(+)-catechin (C)

(-)-Epigallocatechin (EGC)



(-)-Epicatechin (EC)

(-)-Epigallocatechin gallate (EGCG)



(-)-Epicatechin gallate (ECG)

(-)-Gallocatechin (GC)

FIGURE 1 Major catechins in tea.

Caffeine has been reported to be present in dry weight basis at 3–4%. It is soluble in water. Its mild stimulation and astringent effects are considered to be one of the reasons for the popularity of tea.

The most important and characteristic components in tea are the polyphenols. The total content of tea polyphenols expressed as percentage of dry weight leaf is around 20–30%. They are the key compounds that determine the taste and color of infusion and have proved to have beneficial effects on human health. The most important compounds in tea polyphenols are the catechins. The content of catechins in tea is around 12–24% and represents more than 50% of the total amounts of tea polyphenols. Six kinds of catechin compounds were isolated from tea. They are the various derivatives of catechins and gallic acid, including (i) catechin (C), (ii) epi-catechin (EC), (iii) gallocatechin (GC), (iv) epicatechingallate (ECG), (v) epigallocatechin (EGC), and (vi) epigallocatechingallate (EGCG). Generally, the content of the latter three catechins are relatively high. Their structure is listed in Fig. 1. These catechin compounds condense to theaflavin and thearubigin during the manufacturing process of black tea. The formation of these compounds makes the infusion orange-red in color.

A. Chemical Basis of Tea Tasting

The taste of tea is based on the taste threshold value of chemical components in tea and the reaction of sensory organs to these components. The compounds which play the major role in taste are tea polyphenols, amino acids, and polysaccharides. The most important standard for the green tea is "freshness and fullness." The "freshness" is a reflection of amino acids, and the "fullness" is a reflection of the suitable ratio of amino acids and tea polyphenols. The standard of black tea is "strong, fullness, and briskness." The catechins and theaflavin are the most important compounds determining the tasting of black tea. "Strong" depends on the content of water extracts.

Briskness and fullness of taste mainly depend on the suitable ratio of caffeine, theaflavin, and amino acids. The conjugation of these compounds and caffeine creates the astringency feeling and strong taste.

B. Chemical Basis of Tea Color

Different kinds of tea have distinct color. This includes the color of made tea and color of infusion. The color is based on certain chemical compounds. For example, the color of green tea is mainly determined by the chlorophyll and some flavone compounds, such as vitexin and isovitexin. Chlorophyll a is deep green in color and chlorophyll b is yellow-green in color. So, the different proportions of these two chlorophylls constitute the different grade of green color. The color of black tea is black in made tea and orange-red in infusion. These colors are formed by the theaflavin and thearubigin which are polymerized by catechins. Theaflavin is yellow in color and thearubigin is red in color. Different ratios of these two compounds constitute the different degrees of color. If the catechins are overoxidized, the theafluvin (fluvin = brown) is formed which causes the infusion to be an unpleasant dark-brown color. Semifermented Oolong tea is generally dark green–brown color in made tea and yellowish red color in infusion. It is due to the fewer oxidized products of polyphenols.

C. Chemical Basis of Tea Aroma

Tea aroma constitutes a group of flavor compounds. According to the combination of various flavor compounds, the aroma characteristic of various kinds of tea is formed. Up to now, more than 500 flavor compounds were identified in tea, although they existed only a small amount (0.03–0.05% in fresh leaves on dry basis, 0.005–0.01% in green tea, and 0.01–0.03% in black tea). These compounds play an important role in determining the quality of tea. Some of these flavor compounds exist in the intact fresh leaves; however, most of them are formed during the processing process. Alcohols are the greatest flavor components in fresh leaves. There are more than 230 identified flavor components in green tea with the alcohols and pyrazines in the greatest proportion. Alcohols are contained in the intact fresh leaves, but pyrazines are formed during the drying process. Four hundred four flavor compounds were identified in black tea, which include the alcohols, aldehydes, ketones, and ethers. With regard to semifermented tea (such as Puo-chong tea), the alcohols and ketones are the most abundant, especially geraniol, jasmone lactone, nerolidol, indole, etc. Those compounds make the characteristic floral flavor. There were 48 flavor compounds identified in Oolong tea. In the Oolong because of heavy fermentation, linalool and its oxidative products and the benzyl alcohol are the most abundant.

VII. Tea and Human Health

In addition to the best-known effects of relieving fatigue and sobering the mind, it has been proved by modern medical research that tea also possesses the following effects:

Prevention from tooth-caries: It was proved that the fluorine contained in tea are an effective anticary. A study carried out in Japan in which subjects drank 100 ml tea infusion containing 1 g made tea (corresponding to 0.35 ppm F) per day. Results showed that the percentage of caries decreased 19.5–21.3%. Besides the fluorine, tea polyphenols (especially the theaflavin) inhibit activity of glucosyltransferases excreted by teeth-decaying bacteria (*Streptococcus mutans*). Therefore, the transforming process from sucrose to mutan was inhibited, thus minimizing the opportunity of adhension of bacteria on the surface of the tooth-bed.

Antimicrobial action: Use of tea as an anti-inflammatory therapy can be traced back to ancient China. Green tea and black tea showed broad bacteriostatic spectrum *in vitro* including the *Salmonella paratyphi, S. typhi, Vibrio cholera, Shigella dysenteriae*, etc. Besides, it can also inhibit or neutralize the toxin formed by bacteria, such as *Cholera* toxin, *Cholera hemolysia, Staphylococcus aureus* A toxin. Green tea showed the most potent bacteriostatic action among the various kinds of tea. The active components of this action are catechins, especially EGCG.

Hypertension and blood-glucose depressing action: It was proved that ECG, EGCG, and theaflavin have a notable blood tension depressing effect. A new type of tea (Gabaron tea) was developed in Japan by anaerobic treatment of fresh leaves and it was found that the tea contained a large amount of γ-aminobutyric acid. According to the clinical experiment, it showed a significant hypertension depressing effect.

High blood-glucose is a biochemical expression of diabetic patients. A complex of tea EGCG and aluminum hydroxide showed a notable blood-glucose depressing effect, which is comparable to that of Tolbutamide, a well-known blood-glucose depressing medicine. A mixture of polysaccharide compounds and diphenylamine isolated from tea was proved effective in the curing of diabetes.

Effect on cardiovascular disorder: High level of blood cholesterol induces deposit of lipids on vessel walls and causes obstructed coronary arteries, atherosclerosis, and the formation of thrombus. So, decreasing the level of blood lipid is the basis for controlling atherosclerosis and other cardiovascular disorders. Investigation showed that EGCG and ECG decrease the level of total cholesterol, free cholesterol, total lipid, and triglyceride in plasma and liver significantly. Catechin, theaflavin, and thearubigin possess the actions of anticoagulation of blood platelet, anti-hemagglutination, and the promotion of fibriolysis. The clinical experiment using the extract of Tu-cha, Oolong, and green tea showed effectiveness in the prevention of atherosclerosis.

Anticarcinogenic and antimutagenic activity: Scientists in various countries have carried out much research on the anticarcinogenic and antimutagenic effects of tea since the end of the 1970s. Subjects were administered different tea materials (including fresh leaves extract, green tea extracts, EGCG, ECG, tea polyphenols, etc.) orally and treated with various potent carcinogens simultaneously. All tea materials showed anticarcinogenic activity to various degrees. Even when a low concentration of 0.05% tea polyphenols was orally administered, significant anticarcinogenic activity was also exhibited. These positive results have been reported on many kinds of cancer including skin cancer, liver cancer, lung cancer, stomach cancer, intestine cancer, etc.

With regard to the mechanism on the anticarcinogenic and antimutagenic activity of tea, it was proved that tea not only had a dismutagenic and bioantimutagenic activity, but also had inhibitory effects on both stages of initiation and promotion of carcinogenesis.

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Temperate Hardwoods

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- I. Introduction
- II. Forest Associations of the Eastern United States
- III. Presettlement versus Present-Day Conditions
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Glossary

Clear-cutting Removal of the entire forest by logging for the purpose of timber procurement and regenerating light demanding species in the next stand

Climax Final stage or end point of succession resulting in a self-perpetuating forest community comprised of generally shade-tolerant species

Crown classes Vertical position of a tree in the forest canopy, generally classified as dominant, codominant, intermediate, or overtopped

Deciduous Trees that drop their leaves at the end of each growing season

Forest ecology Study of the interrelationships of forest organisms to one another and the environment

Forest type Unit of forest vegetation that is essentially uniform in general appearance and vegetation structure and composition

Gap-phase species Plant species whose successful regeneration or, in the case of trees, overstory recruitment depends on periodic small-scale disturbances that create holes in the forest canopy and increase light to the forest floor

Succession Gradual change which occurs in vegetation in an area over time in which one seral stage replaces another, leading to the end point of succession or climax

Soil The weathered superficial layer of the earth's crust with which is intermingled living organisms and the products of decay

In the broadest sense hardwoods include all tree species in the class of seed plants called Angiosperms, which have seeds enclosed in a developed ovary or fruit. The other major class of seed plants is the Gymnosperms which means "naked seeds," because they are borne on the surface of an appendage and not enclosed in a fruit. Gymnosperms also include many tree species such as pines, spruces, firs, redwoods, and cypress. Angiosperms are divided into two subdivisions—the dicotyledons (two seed leaves) and the monocotyledons (one seed leaf). Monocotyledon families include grasses, orchids, and palms and are generally devoid of tree species, with the exception of certain palm species. Thus, dicotyledonous Angiosperms are the subdivision with almost all of the hardwood tree species. While most research on this subject has been conducted with hardwoods in the temperate regions of the northern hemisphere, they actually occur in most regions of the world, including the equatorial regions, southern hemisphere, and, to a lesser extent, arid, desert environments. They are a very diverse class of trees and can grow under a wide range of temperature, light, moisture, and soil conditions. Within the United States well over 100 hardwood species have important economic or social value. Such highly valued species as walnut, cherry, oak, maple, and hickory are all hardwoods. Historically hardwood forests have represented the primary commercial natural resource in developing countries.

I. Introduction

This article focuses on hardwood forests within the temperate region of the northern hemisphere. In particular, we emphasize the phytogeography and ecology of forests within eastern North America, including climatic, edaphic, and physiographic factors associated with the major forest types, but also discuss hardwood forests within the western United States, Europe, and Asia. For eastern North America, pre-European settlement composition will be described where available, and the effects of disturbance on forest composition and successional relationships are discussed for the major vegetation types.

Temperate hardwood forests of the eastern United States dominate the region from east of the 95th meridian and between 28°N and 48°N latitudes. Geographically, they stretch from the northern tip of Minnesota eastward to central Maine, southward to northcentral Florida, and westward into eastern Texas. Forests of the region are primarily deciduous, although conifer-dominated forests occur in the northeastern, northcentral, and southeastern portions of the biome. Eastern woodlands have a wealth of species due to differences in topography, climate, soils, geological history, disturbance regimes, and land utilization that vary from region to region. Forests typically experience moderate average annual temperatures throughout four distinct seasons. These areas experience a variety of growing season lengths ranging from less than 90 days in northern Wisconsin to 300 days in the southeastern Coastal Plain. Due to the impacts of man, hardwood forests within the last 300 years have been altered to the point where virtually none of the original forest remains undisturbed. Different portions of the landscape have been harvested, burned, and stripped of topsoil and nutrient reserves. Due to their resiliency, however, new hardwood forests have developed following the catastrophic disturbances, although species composition may be significantly different than that in the original forests.

Much of the initial information concerning presettlement forest conditions and present-day forest composition in eastern North America is derived from the extensive work of Dr. E. Lucy Braun. Eastern hardwood forests were originally divided by Braun into nine major associations. For the purpose of this article we have divided the forest into six distinct associations based on the dominant species in each location: northern hardwood–conifer, maple–beech–basswood, mixed-mesophytic, oak–hickory, oak–pine, and southern evergreen (Fig. 1).

The different forest types present on a particular site result from many factors, although climate, physiography, and soil type are typically the most important. Eastern forests contain a variety of soil types associated with different physiographic regions (Fig. 2, Table I). Forests in the northeast and the Lake States are typically composed of young acidic spodosols and inceptisols formed from glacial deposits under cool, moist conditions. Mid-Atlantic and midwestern forests are composed of deep alfisols and ultisols which have subsurface clay accumulations. Weakly differentiated inceptisols are also common in these forests. Deep, highly weathered ultisols dominate the entire southeastern region westward into Texas, although localized areas of alfisols and inceptisols are present along the Mississippi River. These soil differences, as well as annual climatic differences, influence species occurrence and distributional limits. Typically, climate becomes warmer from north to south and markedly drier from east to west within the eastern forest region (Figs. 3 and 4).

II. Forest Associations of the Eastern United States

A. Northern Hardwood–Conifer

This northern vegetation type is characterized by diverse physiography, cold, snowy winters, and glacial soils. It forms one of the larger forest associations, encompassing most of the New England, Adirondack, and Superior Upland physiographic provinces in addition to the northern portions of the Central Lowland and Appalachian Plateau provinces (Fig. 1). Several coniferous species including eastern hemlock (*Tsuga canadensis*), eastern white pine (*Pinus strobus*), red pine (*P. resinosa*), and jack pine (*P. banksiana*) occupy this transition zone between the conifer-dominated boreal forests to the north and deciduous forests to the south. Deciduous species such as sugar maple (*Acer saccharum*), red maple (*A. rubrum*), northern red oak (*Quercus rubra*), American beech (*Fagus grandifolia*), basswood (*Tilia americana*), and yellow birch (*Betula alleghaniensis*) form pure hardwood stands or mixed stands with conifers. A mix of paper birch (*B. papyrifera*), bigtooth aspen (*Populus grandidentata*), and quaking aspen (*P. tremuloides*) is also important throughout much of the Lake States.

Hardwoods in this association generally inhabit mesic sites consisting of moderately well-drained to well-drained soils of medium to heavy texture. In addition to spodosols and inceptisols, hardwood species also inhabit sites composed of alfisols in the aspen-birch dominated portions of the Lake States. Alfisols

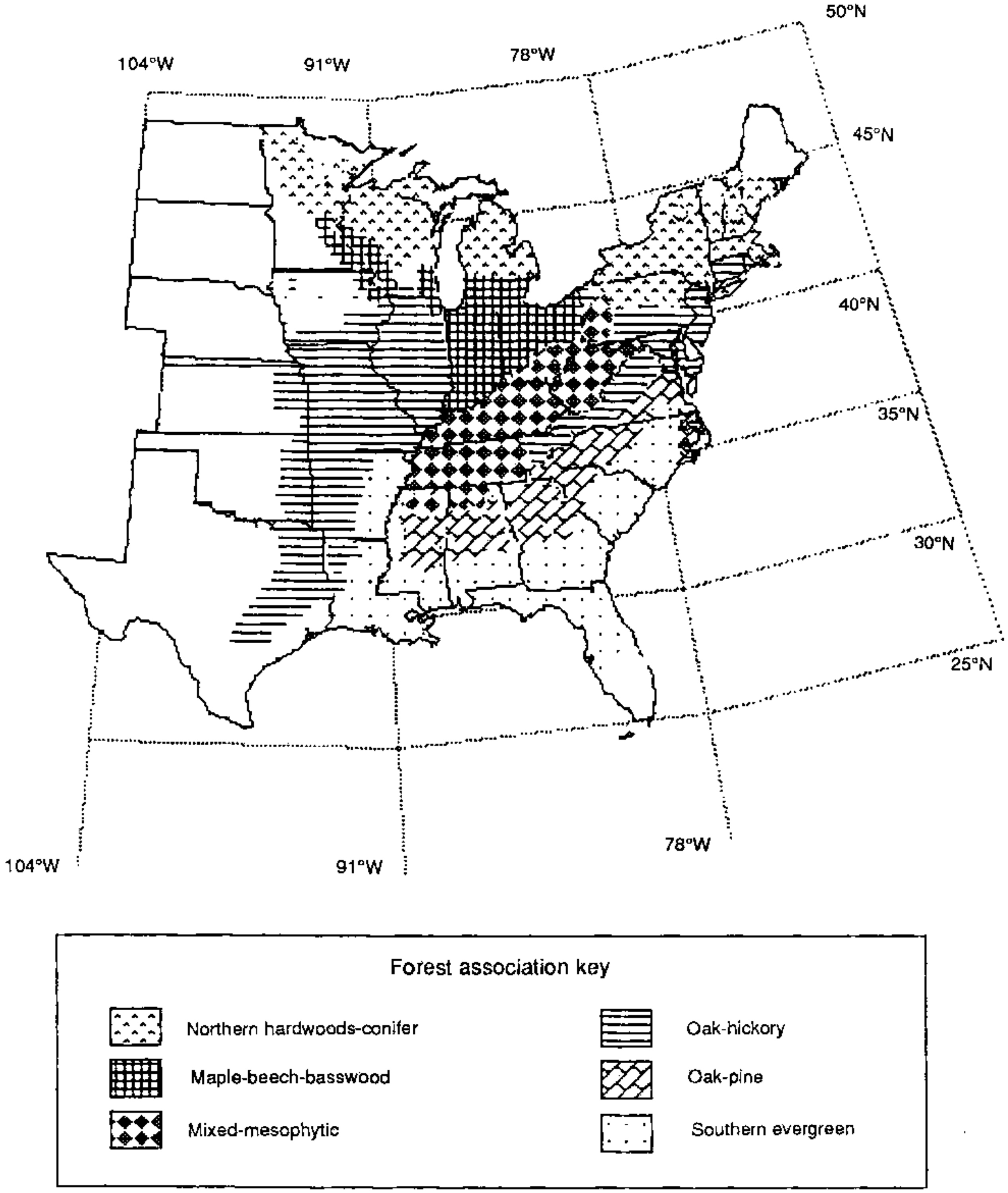

FIGURE 1 Major vegetation associations within the eastern United States.

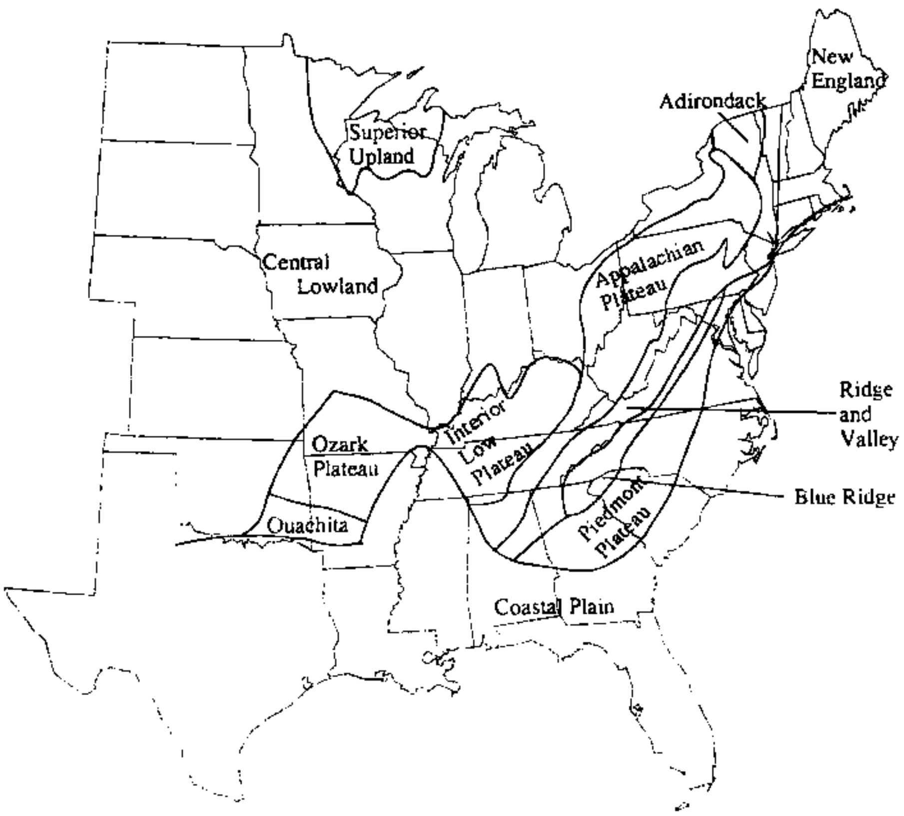

FIGURE 2 Major physiographic provinces in the eastern United States [Adapted from Barnes, B. V. (1991). Deciduous forests of North America. *In* "Ecosystems of the World." 7. "Temperate Deciduous Forests" (E. Rohrig and B. Ulrich, eds.), pp. 219–344. Elsevier Science, New York].

have subsurface horizons high in bases and clay accumulation and therefore are more fertile than spodosols and inceptisols. Hard, impermeable subsurface layers, or fragipans, are also common in alfisols throughout the northeast, resulting in poorer drainage and more mesic site conditions. Excluding hemlock, conifers tend to inhabit dry, fire-prone environments such as eskers, dry outwash sands, and rock outcrops. However, white pine can also be found occupying swamps and mesic ravines as well as former old-field sites throughout New England. Young spodosols or inceptisols formed from Wisconsin-age glacial deposits are typical soils in this type. Similar to spodosols, inceptisols are acidic in nature, but have weakly differ-

TABLE I

Forest Associations, Physiographic Provinces, and Major Soil Orders within Eastern Hardwood Forests[a]

Forest association	Physiographic province(s)	Dominant soil order
Northern hardwoods–conifer	New England; Adirondack Central Lowland; Appalachian Plateau; Superior Upland	Spodosols; Inceptisols; Alfisols
Maple–beech–basswood	Central Lowland	Alfisols
Mixed-mesophytic	Appalachian Plateau; Interior Low Plateau	Alfisols; Ultisols; Inceptisols
Oak–hickory	Ozark Plateau; Central Lowland; Appalachian Plateau; Ridge and Valley; Blue Ridge	Ultisols; Inceptisols
Oak–pine	Piedmont Plateau; Coastal Plain	Ultisols
Southern evergreen	Coastal Plain	Ultisols; Inceptisols

[a] Adapted from Orwig and Abrams (1993). Temperate forests of the eastern United States. *In* "Conservation and Resource Management" (S. K. Majumdar, F. W. Miller, D. E. Baker, E. K. Brown, J. R. Pratt, and R. F. Schmalz, eds.), pp. 97–116. Pennsylvania Academy of Science.

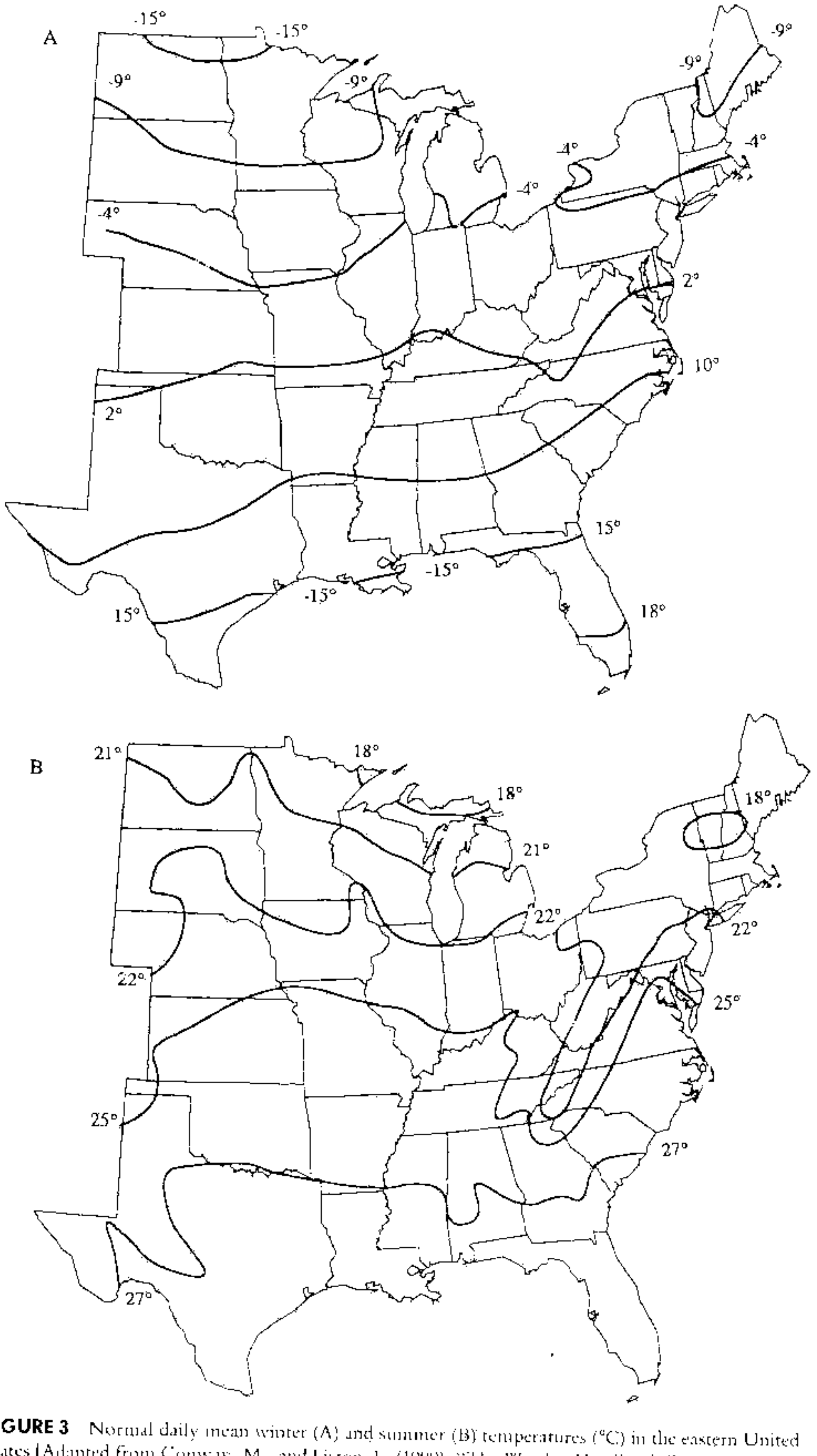

FIGURE 3 Normal daily mean winter (A) and summer (B) temperatures (°C) in the eastern United States [Adapted from Conway, M., and Liston, L. (1990). "The Weather Handbook." Conway Data, Inc., Norcross, GA].

FIGURE 4 Mean annual precipitation (cm) by state [National Climate Data Center (1990). "Comparative Climatic Data for the United States through 1989." Asheville, NC].

entiated horizons with little accumulation of clay or iron.

B. Maple–Beech–Basswood

This association includes both the beech-sugar maple and sugar maple-basswood regions described by Braun (1950, "Deciduous Forests of Eastern North America." Hafner Press, New York). Located within the Central Lowland physiographic province and the northern fringes of the Appalachian Plateau, mesophytic forests of this association are strictly limited to areas of Wisconsin glaciation (Fig. 1). The climate is humid continental with summers being generally warmer than those of the nearby northern hardwood forests. Shade-tolerant sugar maple is the prominent species throughout the region, as it shares overwhelming overstory dominance with American beech on the gently rolling till plains of Ohio and Indiana, and with American basswood (*T. americana*) within the Driftless section located in southwestern Wisconsin, northwestern Illinois, northeastern Iowa, and southeastern Minnesota. Common associates of this association include northern red oak, slippery elm (*Ulmus rubra*), American elm (*U. americana*), red maple, tulip poplar (*Liriodendron tulipifera*), and occasionally white ash (*Fraxinus americana*), black cherry (*Prunus serotina*), and eastern hemlock. Understory vegetation generally consists of seedlings and saplings of the dominant overstory trees and associated species. Because of their shade tolerance, sprouts of beech and basswood, along with sugar maple seedlings can establish themselves in the forest understory. Prior to spring leaf expansion, ephemeral herb species are locally abundant, capturing the early season sunlight. Swamp and bottomland forests throughout many northern forests are dominated by American elm, silver maple (*Acer saccharinum*), yellow birch, larch (*Larix laricina*), and northern white cedar (*Thuja occidentalis*).

Maple–beech mixtures inhabit sites which are composed primarily of mesic alfisols. These soils are well-drained to moderately well-drained, fertile silt or clay loams. Sites within this association remain moist throughout the growing season as a result of soil texture and relatively flat topography. This favorable climate aids in tree growth and reduces the risk of natural and anthropogenic fires. Maple–basswood sites are slightly drier and vary from areas of fine-textured glacial drift in central Minnesota to nutrient-rich loess (wind-deposited loamy soils) sites in southern Wisconsin.

C. Mixed-Mesophytic

This region was originally classified separately as mixed and western mesophytic forests and is characterized by high structural complexity and species diversity. The vegetation contained within the Appalachian Plateau and the Interior Low Plateau regions is one of the most floristically rich collections of overstory species in North America . The broad classification of this group is required due to the highly varied dominance of many different overstory species, commonly 25 tree species or more per hectare. The association stretches southward from the Appalachians of western Pennsylvania and eastern Ohio through West Virginia and into the Cumberland mountains of Kentucky and Tennessee (Fig. 1). Yellow buckeye (*Aesculus octandra*), white basswood (*Tilia heterophylla*), and cucumbertree (*Magnolia acuminata*) are characteristic indicator species whose limits help define the southern and western boundaries of this vegetation type. Additional overstory associates include American beech, tulip poplar, sugar maple, black cherry, American basswood, northern red oak, white oak (*Quercus alba*), white ash, and eastern hemlock. Similar to the overstory, a large assemblage of species comprises the understory layers including redbud (*Cercis canadensis*), sourwood (*Oxydendron arboreum*), dogwood (*Cornus florida*), witch hazel (*Hamamelis virginiana*), hornbeam (*Ostrya virginiana*) and ironwood (*Carpinus caroliniana*).

A variety of habitats ranging from exposed ridges and convex slopes, to protected valleys and mountain coves facilitate the wide array of species found in this association. Perhaps more important are the long, warm growing seasons and the deep, melanized soils which comprise many of these forests. Deciduous mull litter composed of a mixture of organic matter and mineral soil is abundant throughout the association. The humus-darkened soils are a collection of inceptisols, alfisols, and ultisols and are considered to be some of the most productive soils on the continent. The deep alfisols in southwestern Pennsylvania and northwestern West Virginia contain a high base status because they have been formed from shale, limestone, and calcareous shale bedrock. Local ultisols are also deep, moist soils, although they contain a much lower base status because they have been derived from acid sandstones, shale, and phyllite. These unglaciated soils also have thin subsurface accumulations of clay and weatherable minerals.

D. Oak–Hickory

Immediately east and west of the mixed mesophytic association lies the oak–hickory association. The original oak–hickory and the oak–chestnut regions of Braun are included in this association, making it the largest eastern forest association (Fig. 1). Former oak–chestnut forests are now oak–hickory mixtures due to the eradication of overstory chestnut (*Castanea dentata*) by chestnut blight disease during the early part of this century. By the early 1930s, the fungal parasite, *Endothia parasitica*, had killed virtually all mature chestnut trees throughout most of its range. A large, western portion of this vegetation type extends from the Texas Coastal Plain north through the Ouachita and Ozark Plateau provinces into the Central Lowland Province (Fig. 1). Oak-hickory forests may also be found in portions of southern Minnesota, Wisconsin, and Michigan. Vegetation growing in close proximity to the tallgrass prairie region may form a forest–prairie transition type consisting of scattered, open-grown oaks with a grassy understory in Missouri, Iowa, and eastern Nebraska and Kansas. Eastern portions of these forests presently stretch from the previously glaciated sections of southern New England southward along the Ridge and Valley and Blue Ridge physiographic provinces into western North Carolina and eastern Tennessee (Fig. 1).

White oak maintains high, widespread importance throughout the oak-hickory association. A variety of additional oak species comprise overstory positions in different geographic locations within this type. Well-developed oak-hickory forests dominate the more xeric landscape located west of the mixed-mesophytic association. In addition to the ubiquitous white and black (*Q. velutina*) oaks, prominent southern species in the Ozark and Ouachita provinces include post oak (*Q. stellata*), blackjack oak (*Q. marilandica*), and Shumard oak (*Q. shumardii*). In the Central Lowland section, bur oak (*Q. macrocarpa*), northern pin oak (*Q. ellipsoidalis*), and chinkapin oak (*Q. muehlenbergii*) assume greater importance. Dogwood is a common understory species along with persimmon (*Diospyros virginiana*), redbud (*C. canadensis*), serviceberry (*Amelanchier* spp.), pawpaw (*Asimina triloba*), and red mulberry (*Morus rubra*). Oak savannah woodlands are common in the western Central Lowlands province, where xeric conditions preclude the formation of closed forests. The most successful upland species on these savannas include drought-tolerant post oak, blackjack oak, bur oak, black oak, white oak, and black hickory (*C. texana*).

Important overstory species east of the mixed-mesophytic forest type include red oak, black oak, chestnut oak (*Q. prinus*), and scarlet oak (*Q. coccinea*). Tulip poplar, red maple, and various hickories including pignut (*Carya glabra*), mockernut (*C. tomentosa*), bitternut (*C. cordiformis*), and shagbark (*C. ovata*) commonly share canopy dominance with oaks. Common understory trees include dogwood, sassafras (*Sassafras albidum*), red maple, witch hazel (*H. virginiana*), and tupelo (*Nyssa sylvatica*). In addition, short-lived chestnut sprouts are still locally abundant in many eastern forests. Ericaceous shrubs such as *Vaccinium*, *Kalmia*, and *Rhododendron* spp. are also prevalent in oak–hickory understories on acidic sites. Since elevation is highly variable within this association, vegetation common in mixed-mesophytic, maple–beech–basswood, and northern hardwood forests may be found in various amounts on steep slopes, ridges, and mountain coves. Characteristic bottomland associates of this vegetation type include sycamore (*Platanus occidentalis*), river birch (*Betula nigra*), boxelder (*Acer negundo*), red maple, and various willows (*Salix* spp.).

Climatic, topographic, and edaphic differences impact the variety of species observed in different locations within this vegetation type. Oak–hickory mixtures of the western Ouachita and Ozark provinces are comprised primarily of ultisols, although limestone and dolomite are also common soil constituents of the plateau regions. Similar to northern hardwood sites, oak forests of the northern Central Lowlands contain sandy glacial tills and outwash plains. Eastern oak–hickory forests experience more precipitation than western portions of the association and, therefore, contain more mesic species on upland sites. The majority of eastern oak forests are found on characteristically mountainous terrain ranging from gently sloping to steep sites comprised of inceptisols, ultisols, or a mixture of both. Moist valley floor sites typically contain limestone-derived soils, while many of the dry ridges and upper slopes contain soils originating from highly weathered, acidic sandstone or shale.

E. Oak–Pine

This region could be considered an eastern extension of the oak–hickory association, although the codominance of pine species characterizes this association. The majority of this vegetation type resides within the gently rolling Piedmont Plateau province which encompasses Virginia, the Carolinas, and portions of Georgia, as well as the Coastal Plain forests of Alabama and Mississippi (Fig. 1). Common oak and hickory species found in eastern oak–hickory forests are the dominant canopy associates along with a mixture of transitional, even-aged pine forests containing loblolly pine (*Pinus taeda*), shortleaf pine (*P. echinata*), and Virginia pine (*P. virginiana*). Species such as willow oak (*Q. phellos*), sweetgum (*Liquidambar styraciflua*), and tulip poplar obtain local importance throughout the region, whereas longleaf pine (*P. palustris*) is locally important in Alabama. In addition to the abundant dogwood, common understory species include sourwood, tupelo, red maple, and American holly. Similar oak–pine mixtures are also found within Coastal Plain forests of New Jersey, Delaware, and Maryland. Interesting variants of this vegetation type are found in the fire-prone pine barrens of New Jersey, Cape Cod, and Long Island which are dominated by pitch pine (*P. rigida*), and occasionally shortleaf pine, in association with dense, short-statured scrub oaks (*Q. ilicifolia* and *Q. prinoides*).

Climatically, this association is very similar to that of the southern evergreen association, experiencing relatively mild winters, hot summers, and long growing seasons of up to 240 days. Temperatures, however, are typically cooler in the oak–pine type (Fig. 3). Gentle slopes comprised almost exclusively of weathered ultisols prevail throughout this vegetation type. These soils are predominantly acidic, sandy loams derived from crystalline and metamorphic rock parent materials.

F. Southern Evergreen

This vegetation association is confined to the relatively young Coastal Plain, encompassing the entire southeast from Virginia to the Gulf Coastal areas of Texas (Fig. 1). Longleaf pine is the characteristic species along with the evergreen angiosperms, live oak (*Q. virginiana*) and evergreen magnolia (*Magnolia grandiflora*). Spanish moss (*Tillandsia usneoides*) commonly blankets these forests, accentuating their evergreen character. Additional overstory constituents on more xeric sites include slash pine (*P. elliotii*), loblolly pine, turkey oak (*Q. laevis*), bluejack oak (*Q. incana*), blackjack oak, and sand post oak (*Q. stellata* var. *margaretta*). On more mesic sites, hardwoods such as laurel oak (*Q. laurifolia*), sweetgum, southern red oak, white ash, beech, and tulip poplar become more prominent. Common understory species include American holly, dogwood, ironwood, hornbeam, inkberry (*Ilex glabra*), and saw-palmetto (*Serenoa repens*). Extensive swamp and bottomland forests are also common in southern forests along river floodplains, where sweetgum attains its peak abundance and biomass. Baldcypress (*Taxodium distichum*), swamp tupelo (*N. sylvatica* var. *biflora*), water tupelo (*N. aquatica*), black willow (*Salix nigra*), water hickory (*C. aquatica*) and overcup oak (*Q. lyrata*) flourish in these frequently flooded areas. Additional variations of the southeastern evergreen forest include sand pine scrub, dominated by sand pine (*P. clausa*) and understory scrub oaks (*Q. geminata*, *Q. myrtifolia*, and *Q. chapmanii*), and sandhill vegetation dominated by longleaf pine, slash pine, and turkey oak with a wiregrass (*Aristida stricta*) understory.

Southern evergreen forests experience a mild climate with abundant precipitation distributed evenly throughout the year. Humidities in excess of 70% are common and growing season lengths may exceed 300 days. Gentle topography prevails on the ultisol-derived, sandy uplands. Many sites are seasonally flooded and, therefore, soils typically experience mottling. Clay hardpans are also common in southern ultisols, causing further saturation by impeding soil drainage. Xeric sites are located on sand hills stemming from ancient shorelines in portions of the Carolinas, Georgia, western Florida, and southern Alabama and Mississippi. Broad bottomland forests, including the alluvial plain of the Mississippi River, are composed of younger inceptisols. These seasonally wet soils also experience mottling and have an organic surface horizon.

III. Presettlement Versus Present-Day Conditions

Forest species composition is rarely stable for extended lengths of time because of disturbance factors, climatic changes, and successional dynamics. Present-day composition may significantly differ from forests which existed prior to the settlement of European man in the 17th and 18th centuries. However, since few trees presently remain from that time period, past forest history is often reconstructed from written historical accounts of land surveyors and from palynology, the study of pollen sediments. Original land survey records have been used in northeastern and midwestern states to reconstruct forest composition of the last several hundred years. Surveyors described vegetation encountered along township boundary lines and listed the species of each corner "witness" or bearing tree. Past vegetational composition has also been interpreted from similar metes and bounds land surveys, which were common in southern land-grant states. Despite potential bias due to surveyor preferences for certain tree species, historical records are still an accurate tool for determining presettlement forest composition. Preserved pollen extracted from lake and bog sediments has been used to determine the broad-scale climatic changes and associated vegetational changes of the last several centuries, including shifts from pine and spruce to oak-dominated forests throughout most of the eastern United States. Table II describes presettlement forest conditions which were constructed from land survey records and pollen data from different portions of eastern hardwood forests.

More recent changes in forests have occurred primarily due to anthropogenic disturbances. Therefore, pre- and postsettlement forest composition may differ markedly from region to region. Although some white pine–hemlock–northern hardwood forests have remained relatively unaltered since European settlement, many have undergone dramatic changes as a result of anthropogenic disturbances. Following clear-cutting and burning, former hemlock–birch–maple forests in Wisconsin developed overstories dominated primarily by red oak, a species of typically low importance in presettlement forests. Similarly, red oak importance in Massachusetts increased from 7% in presettlement white pine forests to nearly 20% in present-day forests as a result of clearing and logging. An additional striking example of vegetational change due to logging was recorded in hemlock–hardwood forests of the Allegheny Plateau in Pennsylvania, where black cherry and red maple percentages of 1–5% in presettlement forests increased to 23 and 27%, respectively, in present-day forests.

Mixed-mesophytic and oak–hickory forests are currently devoid of the once-dominant chestnut, as only root sprouts of this blight-infected species remain today. As mentioned previously, former chest-

TABLE II
Presettlement Forest Composition in Various Eastern Hardwood Forests[a]

Forest region	State	Presettlement vegetation
Northeast	ME, VT	Spruce spp., yellow birch, balsam fir, beech, birch spp.
	NY, NH, PA	Beech, hemlock, sugar maple, white pine
North-Central	WI, MI, MN	Hemlock, sugar maple, beech, white pine, yellow birch
	MN	Sugar maple, basswood, American elm
	MI	White oak–bur oak savanna
Midwest	IN	Beech, sugar maple
	IL	White oak, red oak, sugar maple, black oak
	OH	White oak, black oak, beech, chestnut
	KY	Beech, sugar maple, white oak
	IN	Bur oak–black oak savanna
Central Plains	MO	White oak, bur oak, blackjack oak savanna, post oak
	KS	Tallgrass prairie
	OK	White oak, shingle oak
Mid-Atlantic	PA	White oak, black oak, white pine, hickory
	NJ	Oak–chestnut
	VA, NC	White oak, red oak, black oak
Southeastern	Entire Coastal Plain	Longleaf pine
	GA, LA	Longleaf pine, white oak
	FL	Magnolia, beech

[a] Adapted from Orwig and Abrams (1993). Temperate forests of the eastern United States. *In* "Conservation and Resource Management" (S. K. Majumdar, E. W. Miller, D. E. Baker, E. K. Brown, J. R. Pratt, and R. F. Schmalz, eds.), pp. 97–116. Pennsylvania Academy of Science.

nut forests were replaced with a group of species including red oak, chestnut oak, black oak, red maple, sweet birch (*Betula lenta*) and pignut hickory. In addition, eastern oak–hickory forests have undergone repeated logging and clearing since settlement, resulting in maintenance of oak in some forests and increases in oak in others, including former oak–pine forests. Midwestern oak–hickory forests also experienced shifts in species composition during postsettlement years as a result of agriculture and fire exclusion. Only 2600 hectares of oak savanna currently remain of the 11–13 million hectares present at the time of settlement. In Wisconsin, bur oak savannas became closed white oak–black oak forests, while rolling prairies in Kansas expanded to closed chinkapin oak–bur oak gallery forests. Naturally occurring southern oak–pine and southern evergreen forests presently contain less pine and more oak and hickory species than during presettlement times. Because pine species are relatively short-lived and fire frequency has been reduced, the succession without disturbance naturally favors the more shade tolerant hardwoods which become established in the understory.

IV. Disturbance Factors

Historical disturbances such as fire, logging, wind, insects, disease, and animals have played a major role in shaping the structure of many forest communities. Fire has been a naturally recurring force in the majority of temperate forests for thousands of years. In North America, presettlement fires caused by lightning or Indian burning occurred frequently in the Central Plains, mid-Atlantic, and southeastern states. Fires were less frequent but more catastrophical in the upper Lake States and infrequent in northeastern states. Indians used fire for a myriad of tasks including cooking, heating, lighting, hunting game, driving off mosquitos, clearing underbrush, and maintaining grasslands. Although some have debated the extent of Indian burning, it certainly affected local forest composition. Frequent fires during presettlement times presumably affected many forests by eliminating later successional species such as beech and maple, and favoring more resistant oak species. Thus, fire suppression since the beginning of the 20th century has permitted shade-tolerant trees to survive and inhabit understory positions in many forests. [*See* FOREST ECOLOGY; SILVICULTURE.]

Windthrow is another natural disturbance which has influenced forest structure for centuries. Wind disturbances typically cause scattered blowdowns of mature trees, creating canopy gaps and a subsequent release of already established individuals or establishment of new species. This "gap-phase" species replacement is common in old-growth hemlock forests, where slightly less tolerant sugar maple, beech, and yellow birch inhabit overstory hemlock gaps. Although windthrow typically occurs as small-scale localized events, less frequent catastrophic windthrow has occurred historically in forests as a result of tornadoes, hurricanes, or heavy localized thunderstorms. Glaze, or ice storms, and early snow prior to leaf fall have similarly affected forests by killing or damaging many overstory trees and stimulating compositional changes, including accelerating succession by releasing shade-tolerant understory trees.

Logging and land clearing for agriculture have also affected a large proportion of hardwood forests. Remaining tracts of land which have escaped logging or clearing are scattered remnants typically located on rough terrain. In addition to the aforementioned compositional changes that occurred following logging, agricultural abandonment following land clearing of hardwood forests also led to drastic compositional changes in various forest types. Old fields in New England were typically invaded by white pine, while abandoned fields of the southeast were commonly invaded by Virginia, shortleaf, or loblolly pines. Dramatic increases in early successional conifer forests resulted from the large-scale agricultural abandonment in the 1800s and early 1900s, initiating the natural conversion to oak–pine and eventually mixed oak forests seen today.

Considerable changes in forest structure may arise due to pathogens or insects, which can cause localized damage and mortality of tree species or can totally eliminate a species such as chestnut. An additional tree species which was recently eliminated from the overstory of many eastern lowland and mesic forests is American elm. Dutch elm disease, caused by the fungus *Ceratocystis ulmi*, along with phloem necrosis disease, resulted in the demise of this dominant species in the 40 years following its introduction into Ohio from Europe in 1930. Common species replacing elm include hackberry (*Celtis occidentalis*), box elder (*Acer negundo*), black cherry, black ash (*Fraxinus nigra*), red maple, and yellow birch. American elm has not been eliminated from understory positions and should persist for generations by short-lived individuals, as seen to a lesser extent in chestnut. Oak wilt (*Ceratocystis fagacearum*), a vascular disease transmitted by sap-feeding beetles, has historically caused mortality of red and black oaks and a subsequent increase in black cherry in midwestern and north-central forests. In addition, beech bark disease (*Nectria coccinea* var. *faginata*) has resulted in extensive mortality of American beech in northern forests over the past few decades. [*See* PLANT PATHOLOGY.]

Hardwood species are also affected by a variety of insects including the destructive gypsy moth (*Lymantria dispar*), which defoliated over 7 million acres of northeastern deciduous forests in 1990 alone. Widespread defoliation can result in considerable oak mortality and may possibly alter species composition. Additional insect pests which incur heavy localized tree damage include the hemlock woolly adelgid (*Adelges tsugae*), in northern hardwood–conifer forests, and the southern pine beetle (*Dendroctonus frontalis*) in pine forests of the southeast and Gulf Coastal Plain.

In many northern forests, deer have been a common disturbance factor limiting stand development by removing understory vegetation. Following heavy cutting cycles in the late 1800s and early 1900s, white-tailed deer (*Odocoileus virginianus*) populations exploded and severely diminished hemlock and other northern hardwood regeneration. Consequently, a shift in species dominance occurred in Michigan forests from hemlock to sugar maple, whereas in many Pennsylvania hardwood stands that suffered total elimination of understory vegetation, arrested succession from fern and grass species was the result. It has been estimated that deer have been directly responsible for more than 85% of regeneration failures within several forests of the Allegheny Plateau.

V. Western *Populus* Forests

Few of the eastern hardwood species persist west of 97° longitude, which is a north–south boundary from western Minnesota through eastern Texas. Eastern tree species that grow beyond that point are generally found in riparian (river and stream) ecosystems. In these communities, eastern cottonwood (*Populus deltoides* var. *deltoides*) and plains cottonwood (*P. deltoides* var. *occidentalis*) are particularly important. These cottonwood species often grow in association with black (*Salix nigra*) and peachleaf (*S. amygdaloides*) willows, as well as hackberry, green ash, box elder, river birch and slippery elm. In addition, trembling aspen (*P. tremuloides)* grows across the entire North American continent, from Nova Scotia to Alaska and occurs as a mosaic of clonal (sprout origin) forests throughout the western United States. These highly valued forests grow primarily along streams and in wet meadows, but can be found in dry plateaus and mountains. Trembling aspen is intolerant of shade or understory conditions and is perpetuated primarily by root sprouting (called suckering) following periodic burning or cutting. In the absence of such disturbances this short-lived species will be replaced by more shade-tolerant trees such as spruce and fir.

VI. Western Oak Forests

As we discussed earlier oak species are one of the most important genera in eastern hardwood forests. Many different oak species also occur in the western

United States, but often under significantly drier conditions than those in the east. Because of the drier conditions many western oak species exist as shrubs, rather than full-sized trees. In the southwestern intermountain region, gamble oak (*Quercus gambelii*) is the most common oak species. It grows as a shrub or small tree in dense thickets on dry foothills, canyons, and lower slopes. It is slow growing, but its acorns and leaves provide valuable forage for a variety of wildlife in the region. Other oak species in the southwestern United States are Mexican blue oak (*Q. oblongifolia*), Arizona white oak (*Q. arizonica*), and emory oak (*Q. emoryi*).

In contrast to the small stature of these southwestern oaks, the oak woodlands in the West Coast States contain a variety of species that obtain full tree size. Oak woodlands typically occur in the Central Valley and foothills of California and the interior valleys of Oregon. These woodlands are savanna-like in nature, with widely-spaced trees and a grassy understory. The dominant deciduous oak species in these communities are Oregon white oak (*Q. garryana*), blue oak (*Q. douglasii*), California white oak (*Q. lobata*), and Engelmann oak (*Q. engelmannii*). Two evergreen oaks, coast live oak (*Q. agrifolia*) and interior live oak (*Q. wislizenii*), may also be important. Typical of oak savannas in the Central Plains States, these western oak woodlands may be dependent on fire for their survival and perpetuation. Oak species throughout the United States are generally light demanding and do not reproduce well in the shade of their own canopy. Periodic understory burning maintains the open nature of these forests and the grassy understory as well as prevents the successional replacement of oak species by the typical climax of fir and Douglas-fir.

VII. Forests of Europe

Temperate hardwood forests of Europe are classified as mixed conifer–hardwood and are much less species diverse than analogous forests in North America or Asia. The primary hardwood ecosystems are dominated by beech and/or oak. European beech (*Fagus sylvatica*) dominates in the plains, low plateaus, and lesser mountain ranges of central and western Europe. These forests are best developed on slightly acid brown soils, where this species grows in association with sycamore maple (*Acer pseudoplatanus*) and linden tree (*Tilia cordata*). Beech trees tend to be tall and small in diameter and grow in dense forests. This may reflect the fact that trees are of coppice (sprout) origin from frequent cutting for charcoal or fuelwood production and that beech is a highly shade-tolerant species. Nonetheless, like many species that grow in late successional forests, beech often regenerates most prolifically in single tree gaps that temporarily increases light to the forest floor. Episodic increases in light around existing beech trees generally triggers the production of root sprouts, which represents an important mode of regeneration for this species. Beech forest can also occur on leached or podzolic soils and grow with oak (*Quercus petraea* and *Q. robur*). When sites are not suitable for beech due to rocks, slopes, exposure, and drainage, it may be replaced by forests of *Q. robur*, *Carpinus betulus*, *Castanea sativa*, or *Pinus sylvestris*. In the Alps, Pyrenes, and Carpathian mountain ranges, beech forests grow to an elevation of 600 to 1300 m, after which they are replaced by higher elevation fir, spruce, larch, and pine forests.

European oak forests exist when site conditions facilitate periodic burning due to being drier and having dense understories and proper fuel conditions, thus eliminating other temperate hardwoods and perpetuating the fire-adapted oak species. Not surprisingly, mediterranean ecosystems in southern Europe that burn with great regularity are dominated by *Quercus ilex*. Temperate oak forests are dominated by *Q. robur* to the north and east and extend from southern Finland to northern Scotland. *Quercus petraea* has a range similar to that of European beech, while *Q. pubescens* grows from the Mediterranean to Nancy, France, to the Bohemia region of central Europe. *Quercus cerris* occurs from the Atlantic ocean to central and western Europe.

Forests of England are dominated by *Q. robur* on heavy lowland soils, *Q. petraea* on sandy soils, and *Fagus sylvatica* on calcareous soils. Associated species with *Q. robur* include *F. sylvatica*, *Carpinus betulus*, *Tilia cordata*, and *T. platyphyllos*. *Quercus petraea* forests are mixed with *Q. ilex* (which was introduced from southern Europe), *Betula pubescens*, and *B. pendula*. Calcareous woods dominated by beech also contain *Tilia*, *Acer campestris*, *Ulmus glabra*, and *Fraxinus excelsor*. Other tree genera or species important to the forests of England include *Platanus*, *Salix*, *Juglans*, *Acer platanoides*, and *Populus*.

VIII. Forests of Asia

Both Japan and China contain a significant amount of land dominated by cool-temperate and warm-temperate, broad-leaved, deciduous hardwood forests. The dominant genera in these countries are remarkably similar to that of eastern North America, including *Fagus*, *Quercus*, *Acer*, *Fraxinus*, *Populus*, *Betula*, and *Pinus*. Cool temperate forests of Japan are dominated by beech (*Fagus crenata* and *F. japonica*) and the oak, *Quercus crispula*. There are a large number of species mixed in these forests, including many maples (e.g., *Acer mono*, *A. micranthum*, and *A. japonicum*), *Acanthopanax*, *Fraxinus lanuginosa*, *Tilia japonica*, and *Magnolia obovata*. Forests on particularly wet sites may contain *Aesculus*, *Cercidiphyllum*, *Betula*, *Alnus*, and *Cornus*. Warm-temperate hardwood forests in Japan are dominated by mixed oak species and *Castanopsis*. The principal oak species are *Q. gilva*, *Q. salicina*, *Q. acuta*, *Q. glauca*, *Q. myrsinaefolia*, and *Q. sessilifolia*. In some localities evergreen conifers may be present, including species of *Abies*, *Tsuga*, *Podocarpus*, *Torreya*, *Picea*, *Crytomeria*, and *Chamaecyparis*. These species occur on stoney, steep, mountainous habitats and comprise small groups of trees within the hardwood forests. On dry habitats *Quercus phillyraeoides*, with small leathery leaves, may be particularly important. This oak species is the Japanese analogue to *Q. ilex* of southern Europe.

Deciduous hardwood forests of China can be divided into four different forest types: mixed-mesophytic, mixed northern hardwood, birch-dominated, and temperate deciduous broad-leaved. Mixed-mesophytic forests occur in southern China and are dominated by over 50 species of *Acer* and multiple species of *Tilia*, *Betula*, *Carpinus*, *Celtis*, *Fraxinus*, *Quercus*, *Ulmus*, and *Phellodendron*. Over 60 genera are known to exist as canopy tree species in these diverse forests, with no one species acting as a superdominant. Mixed northern hardwood forests located in northern China are represented by more than 20 tree genera, the most important being *Acer*, *Betula*, *Pinus koraiensis*, *Quercus*, *Fraxinus*, *Juglans*, *Maackia*, *Phellodendron*, and *Ulmus*. Birch forests dominated by *Betula ermani*, *B. costata*, *B. dahuria*, and *B. platyphylla* forms the upper altitudinal reaches of temperate deciduous oak forests and mixed northern hardwood forests near Siberia. At higher elevations, below the montane coniferous zone, birch species form nearly pure stands except for occasional *Populus*, *Salix*, and *Sorbus* species. Temperate deciduous broad-leaved forests exist in the subhumid regions of central China in between the mixed-mesophytic forests of the south and the mixed hardwood forests to the north. In general, these forests are dominated by the deciduous oaks *Quercus mongolica*, *Q. dentata*, *Q. liaotungensis*, *Q. acutissima*, *Q. variabilis*, and *Q. serrata* and the evergreen oaks *Q. baronii*, *Q. glauca*, and *Q. spinosa*. Lower elevation oak forests may be mixed with *Celtis*, *Fraxinus*, *Juglans*, *Populus*, *Ulmus*, *Carpinus*, and *Acer*. Most oak forests have their canopy dominated by a single oak species. In drier habitats *Q. mongolica* and *Q. dentata* form open, savanna like stands.

IX. Global Change and Future Forests

As we have discussed above, vegetational change is a dynamic process attributable to many factors including disturbance regimes, site conditions, and prevailing climatic conditions. Climate will probably be the most important factor controlling future vegetational change. Although climatic changes over the past several hundred years have been small, it is predicted that unprecedented climatic change may occur over the next few centuries. Atmospheric carbon dioxide (CO_2) concentrations have risen steadily and are projected to nearly double from the already inflated present levels by the mid-21st century. Increases in CO_2 and other atmospheric trace gases may cause global temperatures to increase several degrees (°C), which could significantly alter forest structure and productivity. Recent predictions based on projected global temperature increases propose declines of spruce and northern pine species. As global temperatures increase, a synergistic effect between vegetation, drought, and fire may occur as the potential for severe fires are predicted to increase, which in turn may lead to increases in vegetation which can tolerate high fire frequency. Therefore, oak and hickory populations are predicted to experience an overall expansion in most temperate forests.

Atmospheric pollutants such as ozone, sulfur dioxide, and nitrogen oxide may also influence future forest composition. These pollutants have been hypothesized to contribute to forest decline in many temperate forests by inhibiting photosynthesis, leaching soil cations, and increasing soil aluminum toxicities. Due to the complexities of our atmosphere and the many interactions present within and among ecosystems, predictions about climatic trends and associated vegetative changes are tenuous at best. Predictive models which take into account species' responses to past environmental changes, potential species' migration rates, and possible climatic feedbacks have been utilized to simulate future scenarios in hardwood forests. More information concerning long-term atmospheric and climatic trends as well as species, population, and ecosystem responses to fluctuating conditions are necessary to accurately predict the future composition of temperate forests of the northern hemisphere. [*See* AIR POLLUTION: PLANT GROWTH AND PRODUCTIVITY.]

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Thermal Processing: Canning and Pasteurization

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- I. Technology Overview of Thermal Processing
- II. Scientific Principles of Thermal Processing
- III. New Developments

Glossary

Aseptic processing Filling and hermetically sealing a previously heat-treated commercially sterile food into a separately sterilized package or container under a sterile environment

Commercial sterilization Relatively severe heat treatment at temperatures above 100°C to inactivate heat-resistant bacterial spores for long-term preservation of foods to be stored at normal nonrefrigerated conditions; heat treatment times and temperatures calculated on the basis of achieving sufficient bacterial inactivation in each food container to comply with public health standards and to insure that the probability of spoilage will be less than some minimum; foods are rendered safe but not "sterile" in the medical sense in that they are not completely free of all possible microorganisms (all references to "sterilization" in this article imply commercial sterilization)

Canning Method of food preservation which results in hermetically sealed containers of food that have been sterilized by heat so they may remain shelf stable over long periods of storage at normal nonrefrigerated storage conditions; the severity of heat treatments needed for this purpose depends upon whether microbial activity is further hindered by low pH and/or water activity of the specific food product

Lethality Reduction in population of target microorganisms as a result of exposure to a lethal temperature history, and expressed as the number of logarithm cycles in population reduction

Slowest heating point Location within a container of food that is last to respond to heat that is penetrating inward from all surfaces, usually the geometric center of the container for solid-packed foods or food containers that are continuously agitated during processing; for containers with liquid products that are held motionless during processing, the slowest heating point may lie somewhat below the geometric center because of naturally occurring convective currents that arise during heating of the liquid contents

Retort Large industrial-sized pressure vessel or cooker in which filled sealed food containers are exposed to pressurized steam for sterilization at temperatures above 100°C

Pasteurization Relatively mild heat treatment at temperatures below 100°C to inactivate heat-sensitive bacterial cells for temporary preservation of foods to be stored under refrigeration

Sterilizing value Time in minutes at a constant reference process temperature that will produce the same lethality as that delivered by the actual temperature history experienced at the slowest heating point in food container during a retort process, and is symbolized by F_0

Thermal process Specifically, the heating of foods in retorts after they have been filled and hermetically sealed in airtight containers for sufficient time and temperature to render the product commercially sterile; generally, any method of heating to accomplish the purpose of heat sterilization or pasteurization

Thermal processing covers the broad area of food preservation technology in which heat treatments are used to inactivate microorganisms to accomplish either commerical sterilization or pasteurization. Sterilization processes are used with canning to preserve the safety and wholesomeness of ready-to-eat foods over long terms of extended storage at normal nonrefrigerated temperature without additives or preservatives, while pasteurization processes are used to extend the refrigerated storage life of fresh foods.

I. Technology Overview of Thermal Processing

A. Sterilization versus Pasteurization

Both sterilization and pasteurization are thermal processes which make use of heat treatments for the purpose of inactivating microorganisms in foods. However, they differ widely with respect to the classification or type or microorganisms targeted, and thus the range of temperatures that must be achieved, and the type of equipment systems capable of achieving such temperatures. Pasteurization is used to inactivate vegetative bacterial cells, food-borne pathogens which have a relatively low heat resistance. These organisms can be effectively inactivated when exposed to temperatures in the range of 75–95°C, which is below the boiling point of water at standard conditions. These are also the organisms of concern when attempting to prolong the safety and wholesomeness of fresh foods intended for limited periods of refrigerated storage. The more highly heat-resistant bacterial spores remain unaffected by pasteurization, and will eventually spoil the food. Thus, pasteurization is a relatively mild heat treatment used in conjunction with refrigerated storage. [*See* FOOD MICROBIOLOGY.]

In order to achieve long-term microbial stability in foods, it is necessary to inactivate the more highly heat-resistant bacterial spores which require temperatures in the range of 110–150°C. These temperatures are well above the boiling point of water at standard conditions, and can only be achieved with the use of water (or steam) under pressure in specialized equipment. Because of the severity of these heat treatments, they also accomplish the objectives of pasteurization, and are capable of rendering the food commercially sterile. Thus, this type of heat treatment is known as sterilization, and much of the article will address thermal processing applied to sterilization of canned foods (canning).

B. Retort Processing

There are two fundamentally different process methods by which canning is accomplished in the food industry. These two methods are known as retort processing and aseptic processing. In retort processing, foods to be sterilized are first filled and hermetically sealed in cans, jars, or other retortable containers; they are then heated in their containers using hot steam or water under pressure so that heat penetrates the product from the container wall inward; both product and container become sterilized together. In aseptic processing, a liquid food is first sterilized outside the container by pumping it through heat exchangers which deliver very rapid heating and cooling rates. Then, the cool sterile product is filled and sealed in a separately sterilized package under a sterile environment at room temperature. Thus, retort processing can be thought of as "in-container" sterilization, and aseptic processing can be thought of as "out-of-container" sterilization. Each of these canning methods will be described more fully.

In retort processing (in-container sterilization), the food to be sterilized is first filled and hermetically sealed in rigid, flexible, or semirigid containers such as metal cans or trays, glass jars, retort pouches or plastic bowls or trays which are then placed within large steam retorts (pressure vessels that work like giant pressure cookers). Once the retorts are full of containers to be sterilized, the retort doors are closed tightly and the air is replaced by hot steam under pressure to achieve temperatures above the atmospheric boiling point of water. A common retort temperature for sterilizing canned foods is 121°C (250°F), at approximately one atmosphere of added internal pressure. After the containers have been exposed to the sterilizing temperature for sufficient time to achieve the desired level of sterilization, the steam is shut off and cooling water is introduced to cool the containers and reduce the pressure, thus ending the process. Once the retort pressure has returned to atmosphere, the doors can be opened, and the processed containers removed for labeling, case-packing, and warehousing to await distribution to the market place.

As would be expected, considerable time, effort, and labor are required to repeatedly unload and reload the retorts after each retort load or batch of containers has completed the sterilization cycle. This is known as a batch retort operation which can become very labor-intensive for large-scale production. Modern food canning plants that produce large volumes of canned foods operate with great efficiency by using continuous retort systems. In continuous rotary retort systems, filled and sealed containers travel in single file along automated conveying tracks into a series of continuous retorts. They enter through a rotating pressure-seal valve that works like a revolving door to maintain the steam pressure inside the retort while introducing container after container from the outside atmosphere at speeds approaching 500 units per minute. Once inside the continuous retort, the containers travel slowly along a rotating helical path (much like being pushed along by riding within the groove

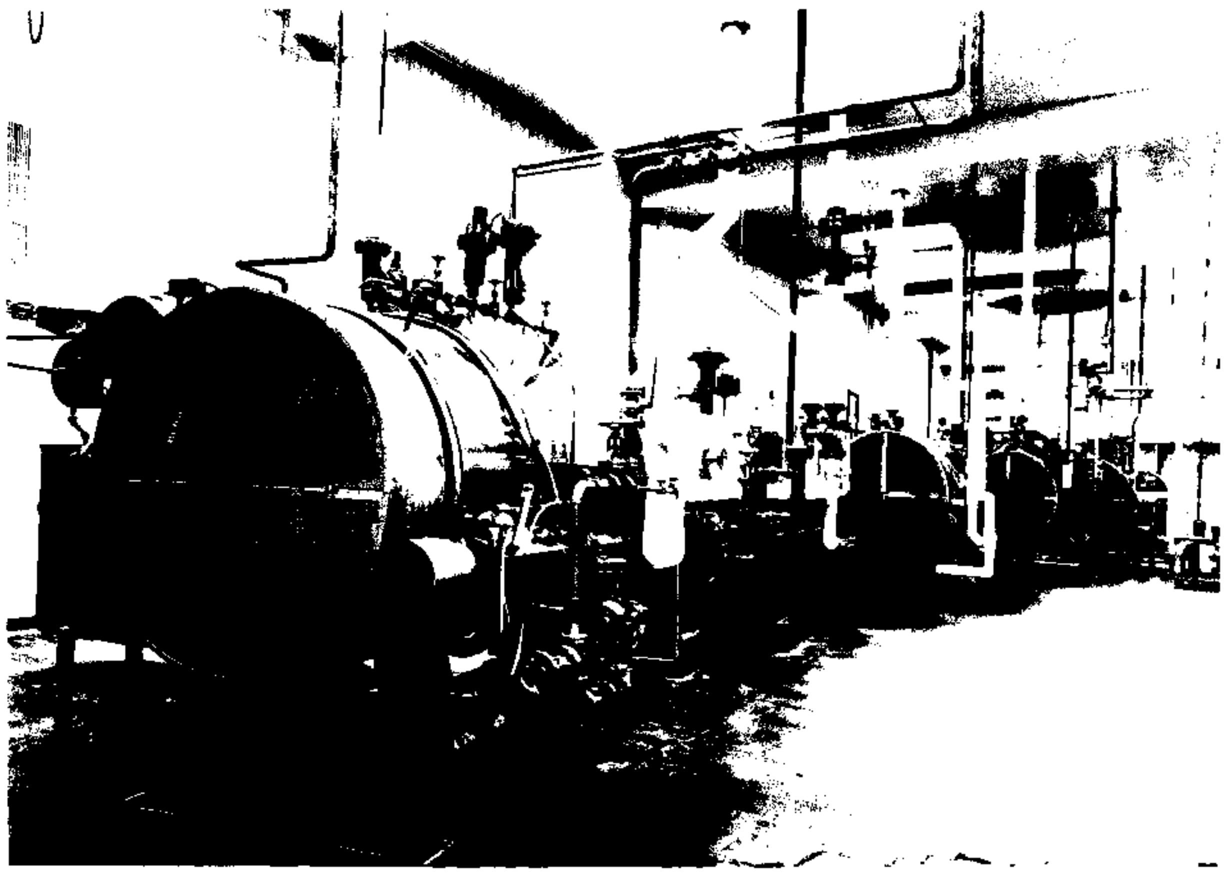

FIGURE 1 Continuous rotary sterilizer system. [Courtesy of FMC Corporation. Reprinted with permission from Teixeira, A. (1992). Thermal process calculations. *In* "Food Engineering Handbook". (Heldman and Lund, eds.). Chapt. 11 Fig. 28, p. 599. Copyright © 1992 by Marcel Dekker, Inc., New York.]

of a rotating screw) until they exit the opposite end of the retort through a similar rotating pressure-seal valve (see Figs. 1 and 2). In a continuous system of this type, the containers move directly from the high pressure steam retort into a cooling retort which is filled with cooling water instead of hot steam to accomplish the cool-down portion of the process. The cool sterilized containers are then conveyed automatically to the labeling, case packing, and warehousing operations as described earlier.

An alternative to the continuous rotary retort system described above is the continuous hydrostatic retort system, which makes use of two U-shaped columns of water over 20 m high separated by a pressurized steam chamber in which the containers are sterilized. Both columns of water are open to the atmosphere at the top and are open to the steam chamber at the bottom. One column serves as the entrance water leg while the other serves as the exit leg. Meanwhile a chainlink-driven conveyor travels continuously through the system carrying cradles of incoming containers up along the outside wall to the top of the inlet water leg and then down the inlet water leg into the steam chamber. The conveyor speed and length of its path within the steam chamber are designed so as to deliver a sufficiently long residence time of exposure to the hot steam so the containers are fully sterilized before they are carried up the exit leg and down the other side where they automatically transfer to the conveying tracks that take them away for labeling, case packing, and warehousing (see Figs. 3 and 4).

C. Aseptic Processing

The retort temperatures and times required to make food microbiologically safe may also cause unavoidable quality degradation. For these heat-sensitive products sterilization temperatures and times are chosen which will produce a commercially sterile product, but with minimum quality degradation. Because in a retort the container is heated from the outside,

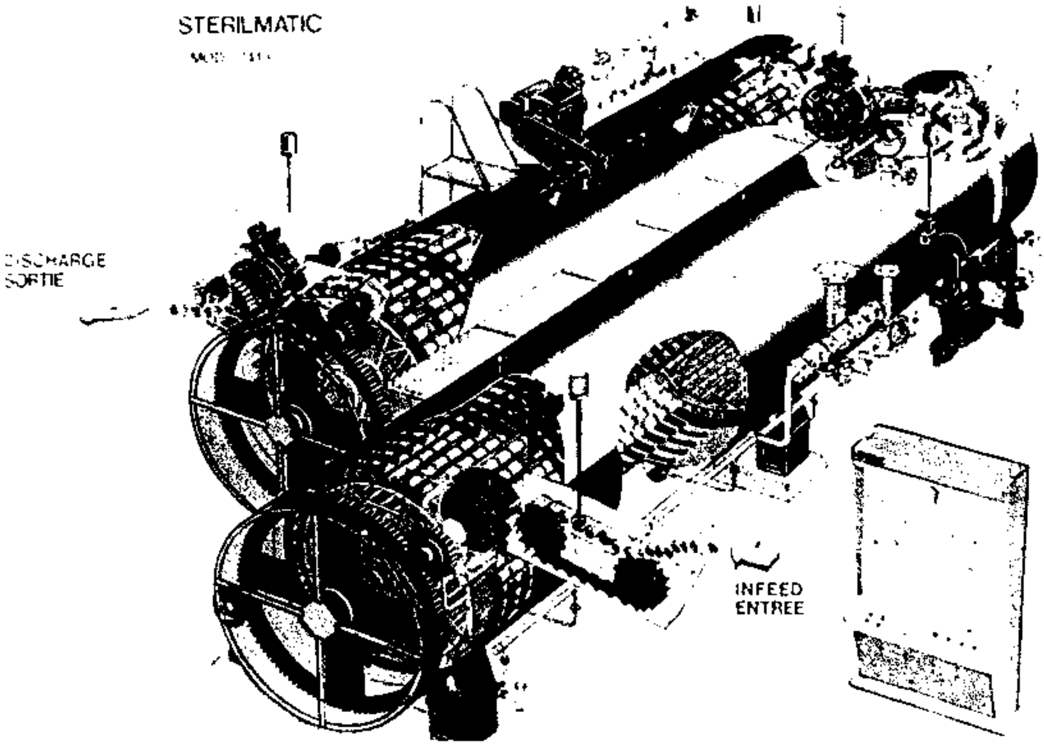

FIGURE 2 Cutaway view of continuous horizontal rotary sterilizer. [Courtesy FMC Corporation. Reprinted with permission from Teixeira, A. (1992). Thermal process calculations. *In* "Food Engineering Handbook" (Heldman and Lund, eds.), Chapt. 11, Fig. 27, p. 598. Copyright © 1992 by Marcel Dekker, Inc., New York.]

it is apparent that the food next to the container wall reaches the process temperature much sooner than the material in the center of the container particularly with solid foods that heat by conduction. As a result, the major portion of the product must be held at an elevated temperature much longer than is necessary to render it sterile while time is being used to assure that sufficient sterilization is reached at the slowest heating point of the container. Obviously the container size, the product consistency, and its ability to conduct heat exerts a very measurable effect on the required time–temperature relationship. Large containers require much longer processing times. Thus, the quality of solid food is generally poorer in larger containers as compared to the same food processed in small containers.

Following the above logic further, it can be reasoned that if the food can be taken out of the container altogether, the distance for heat penetration can be reduced by a minimum if the food can move as a liquid through very narrow tubes or channels in heat exchangers, or exposed directly to hot steam in a fine spray or thin liquid film. This is the concept behind out-of-container sterilization or aseptic processing mentioned earlier. Aseptic processing is essentially limited to liquid foods that can be pumped or sprayed through heat exchangers which are capable of heating the product almost instantaneously to the sterilizing temperature, and cool it down just as quickly. The exposure time that is needed at the sterilizing temperature is achieved by letting the heated product flow through an insulated holding tube of sufficient length before entering the cooling section of the heat exchanger. The main drawback to this processing concept historically has been the difficulty in avoiding recontamination of the cool sterile product from subsequent exposure to the atmosphere or package when attempting to package it for long-term storage. These drawbacks have since been overcome by the development of sophisticated aseptic packaging and filling systems which are capable of forming, filling, and sealing sterile packages with sterile liquid products under controlled sterile environments.

D. Pasteurization Processes

Just as with retort and aseptic methods of canned food sterilization, pasteurization can be carried out by either in-container or out-of-container processes. The main difference from sterilization is that the lower

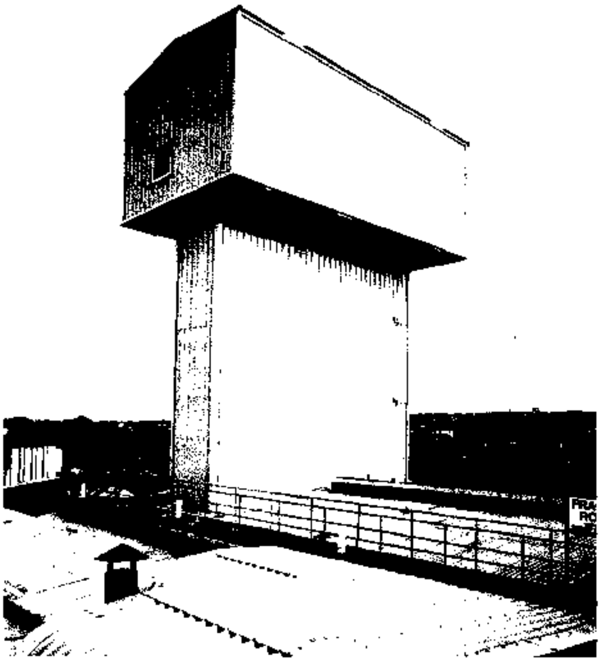

FIGURE 3 Exterior view of continuous hydrostatic sterilizer. [Courtesy FMC Corporation. Reprinted with permission from Teixeira, A. (1992). Thermal process calculations. *In* "Food Engineering Handbook" (Heldman and Lund eds.), Chapt. 11, Fig. 29, p. 600. Copyright © 1992 by Marcel Dekker, Inc., New York.]

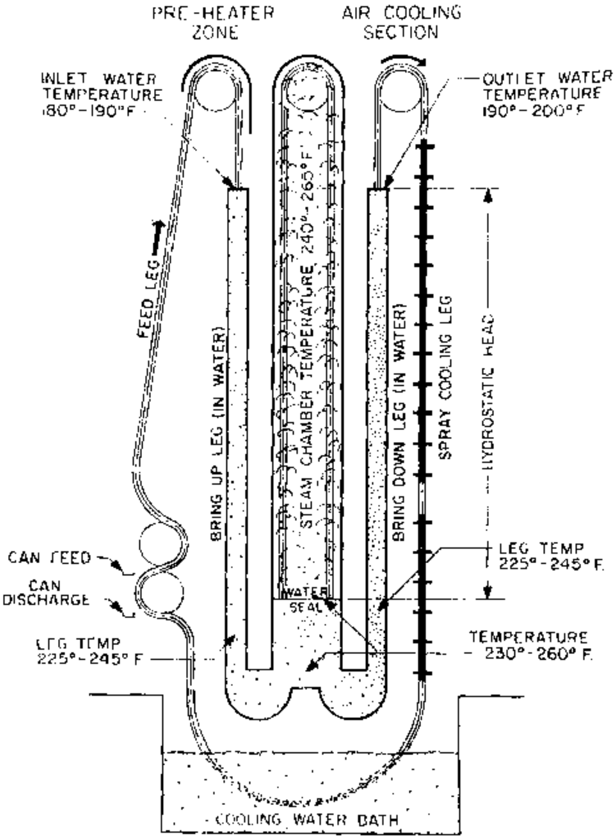

FIGURE 4 Operating schematic of a continuous hydrostatic sterilizer for canned foods. [Reprinted with permission from Teixeira, A. (1992). Thermal process calculations, in "Food Engineering Handbook." (Heldman and Lund eds.), Chapt. 11, Fig. 30, p. 601. Copyright © 1992 by Marcel Dekker, Inc., New York.]

temperatures used for pasteurization do not require the need for operating under pressure. Thus, the equipment systems needed for pasteurization are much simpler in design and easier to operate and maintain.

Normally, liquid foods with delicate heat-sensitive quality attributes like milk and fruit juices are pasteurized out-of-container using high temperature-short time (HTST) heat exchangers to pasteurize with minimum quality degradation prior to filling in clean packages. These HTST pasteurization systems are similar to the aseptic process systems used in sterilization except that they operate at lower temperatures and at atmospheric pressure, and they do not require rigid aseptic filling conditions. Some liquid dairy products, such as dairy cream and coffee whitener, are given a sterilization heat treatment by operating the heat exchanger under pressure to achieve sterilizing temperatures, but are filled into conventional sanitary cartons without aseptic filling systems. Such products are marketed as "ultra-pasteurized" with markedly longer storage life under refrigeration. [*See* DAIRY PROCESSING AND PRODUCTS.]

Less heat-sensitive foods as well as most nonliquid foods are pasteurized in-container much like the retort process for sterilization, except that an open tank of hot or near-boiling water is sufficient, and there is no requirement to use pressure vessels like retorts or autoclaves. A third method of pasteurization, known as "hot fill," makes use of the high pasteurizing temperature reached by the product in a batch tank or mixing kettle as part of the product preparation. The clean empty containers are filled with the hot product and sealed. They are held upright for a few minutes to transfer sufficient heat to the container walls and bottom; they then are inverted for an additional few minutes to complete pasteurization of the container lid and seal area using heat transferred from the still hot product. Most canned fruits, fruit preserves, and acidified (pickled) products are pasteurized in this way.

Note that the food examples given above for the "hot fill" method of pasteurization are nonrefrigerated foods which enjoy long-term storage at room temperature without the use of sterilization heat treatments. That is because they are high-acid foods (pH<4.5) which cannot support the growth of heat-resistant spore forming pathogens. High-acid foods are subject to spoilage principally by yeasts and molds, which have low heat resistance and can be inactivated by pasteurization heat treatments, alone. These are technically canned foods, but are essentially processed by the use of pasteurization technology. That is why it is important to distinguish between high-acid and low-acid canned foods in the context of thermal processing.

II. Scientific Principles of Thermal Processing

A. Important Interrelationships

An understanding of two distinct bodies of knowledge is required to appreciate the basic principles involved in thermal process calculation. The first of these is an understanding of the thermal inactivation kinetics (heat resistance) of food-spoilage-causing organisms. The second body of knowledge is an understanding of the heat transfer considerations that govern the temperature profiles achieved within the food container during the process, commonly referred to in the canning industry as heat penetration.

Figure 5 conceptually illustrates the interdependence between the thermal inactivation kinetics of bacterial spores and the heat transfer considerations in the food product. Thermal inactivation of bacteria generally follows first-order kinetics and can be described by a logarithmic reduction in the concentration of bacterial spores with time for any given lethal temperature, as shown in the upper family of curves in Fig. 5. These are known as survivor curves. The decimal reduction time, *D*, is expressed as the time in minutes to achieve one log cycle of reduction in concentration, *C*. As suggested by the family of curves shown, *D* is temperature dependent and varies logarithmically with temperature, as shown in the second curve. This is known as a thermal-death-time (TDT), curve and is essentially a straight line over the range of temperatures employed in food sterilization. The slope of the curve that describes this relationship is expressed as the temperature difference, *Z*, required for the curve to traverse one log cycle (achieving a tenfold change in *D*). The temperature in the food product, in turn, is a function of the retort temperature (T_R), initial product temperature (T_I), location within the container (x), thermal diffusivity of the product (α), and the time (t), as shown by the heat penetration curves at the bottom of Fig. 5.

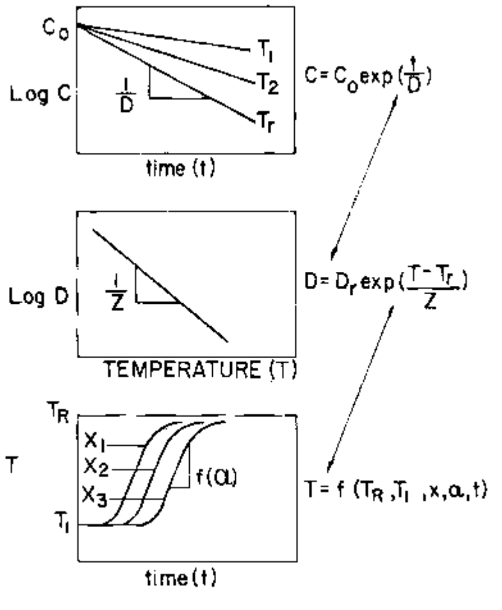

FIGURE 5 Time and temperature dependence of the thermal inactivation kinetics of bacterial spores in the thermal processing of canned foods. [Reprinted with permission from Teixeira, A. (1992). Thermal process calculations. *In* "Food Engineering Handbook" (Heldman and Lund, eds.), Chapt. 11. Copyright © 1992 by Marcel Dekker, Inc., New York.]

Thus, the concentration of viable bacterial spores during thermal processing decreases as a function of the inactivation kinetics, which are a function of temperature. The temperature, in turn, is a function of the heat transfer considerations, involving time, space, thermal properties of the product, and initial and boundary conditions of the process. This interrelationship is illustrated by the functional expressions given in Fig. 5.

B. Microbiological Considerations

When subjected to a lethal temperature, a population of viable bacterial spores will decrease logarithmically at a rate which can be defined by the decimal reduction time (*D*) described earlier in reference to Fig. 5. As shown on the second curve of Fig. 5, *D* is temperature dependent and will take on different values at different temperatures in an exponential relationship, which will appear as a straight line on a semilog plot of *D* versus temperature. This is known as a thermal death time (TDT) curve, shown in more detail in Fig. 6. The slope of this curve reflects the temperature dependency of *D* and is used to derive the temperature dependency factor *Z*, which is expressed as the temperature difference (usually in degrees Fahrenheit) required for the curve to traverse one log cycle, or the

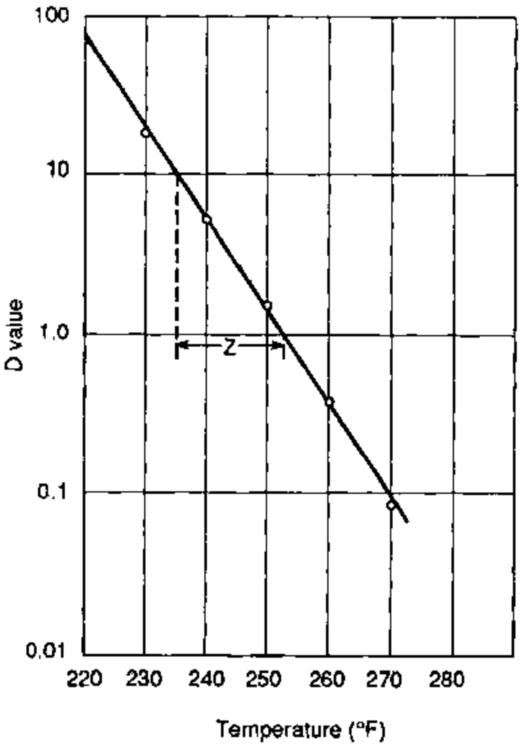

FIGURE 6 Thermal death time (TDT) curve showing temperature dependency of *D* value (decimal reduction time of microorganisms) given by temperature change (*Z*) required for 10-fold change in *D* value. [Reprinted with permission from Teixeira, A. (1992). Thermal process calculations. *In* "Food Engineering Handbook". Chapt. 11, Fig. 6, p. 570. Copyright © 1992 by Marcel Dekker, Inc., New York.]

temperature difference required for a 10-fold change in the *D* value.

Once the TDT curve has been established for a given microorganism, it can be used to calculate the time–temperature requirements for any idealized thermal process. For example, assume a process is required that will achieve a six-log-cycle reduction in the population of bacterial spores whose kinetics are described by the TDT curve in Fig. 6, and that a temperature of 235°F has been chosen for the process. The TDT curve shows that the *D* value at 235°F is 10 min. This means that 10 min will be required for each log cycle reduction in population at that temperature. If a six-log-cycle reduction is required, a total of 60 min is required for the process. If a temperature of 270°F had been chosen for the process, the *D* value at that temperature is approximately 0.1 min, and only 0.6 min (or 36 sec) would be required at that temperature to accomplish the same six-log-cycle reduction.

C. Sterilization *F* Value

The example process calculations carried out using the TDT curve in Fig. 6 showed clearly how two widely different processes (60 min at 235°F and 0.6 min at 270°F) were equivalent with respect to their ability to achieve a six-log-cycle reduction for that organism. Therefore, for a given *Z* value, the specification of any one point on the line is sufficient to specify the sterilizing value of any process combination of time and temperature on that line. The reference point that has been adopted for this purpose is the time in minutes at the reference temperature of 250°F, or the sterilizing *F* value for the process. Since the *F* value is expressed in minutes at 250°F, the unit of lethality is 1 min at 250°F. Thus, if a process is assigned an *F* value of 6, it means that the integrated lethality achieved by whatever time–temperature history is employed by the process must be equivalent to the lethality achieved by 6 min of exposure to 250°F.

To illustrate, the example process calculation using the TDT curve in Fig. 6 will be repeated by specifying the *F* value for the required process. Recall from that example that the process was required to accomplish a six-log-cycle reduction in spore population. All that is required to specify the *F* value is to determine how many minutes at 250°F will be required to achieve that level of log-cycle reduction. The D_{250} value is used for this purpose, since it represents the number of minutes at 250°F to accomplish one log-cycle reduction. Thus, the *F* value is equal to D_{250} multiplied by the number of log cycles required in population reduction, or

$$F = D_{250}\,(\log a - \log b), \qquad (1)$$

where a is the initial number of viable spores and b is the final number of viable spores (or survivors).

In this example, $D_{250} = 1.16$ min as taken from the TDT curve in Fig. 6, and $(\log a - \log b) = 6$. Thus, $F = 1.16(6) = 7$ min, and the sterilizing value for this process has been specified as $F = 7$ min. This is normally the way in which a thermal process is specified for subsequent calculation of a process time at some other temperature. In this way information regarding specific microorganisms or numbers of log cycles reduction can be replaced by the *F* value as a process specification.

Note also that this *F* value serves as the reference point to specify the equivalent process curve discussed earlier. By plotting a point at 7 min on the vertical line passing through 250°F in Fig. 6, and drawing a curve parallel to the TDT curve through this point, the line will pass through the two equivalent process points that were calculated earlier (60 min at 235°F, and 0.6 min at 270°F). Alternatively, the equation of this straight line can be used to calculate the process time (t) at some other constant temperature (T) when F is specified.

$$F = 10^{[T - 250/Z]} t. \qquad (2)$$

Equation (3) becomes important in the general case when the product temperature varies with time during a process, and the F value delivered by the process must be integrated mathematically, such as at the center of a container of solid food.

$$F = \int_0^t 10^{[T - 250/Z]} dt. \qquad (3)$$

D. Heat Transfer Considerations

In traditional thermal processing of canned foods, the situation is quite different from the idealized processes described above. Containers are placed in steam retorts which apply heat to the outside wall. The product temperature cannot respond instantaneously, but will gradually rise in an effort to approach the temperature at the wall followed by a gradual fall in response to cooling at the wall. In this situation, the sterilizing value delivered by the process will be the integrated result of the time–temperature history experienced at the slowest heating point of the container, which is determined by heat penetration tests. The primary objective of heat penetration tests is to obtain an accurate recording of the product temperature at the slowest heating point of the container over time while the container is being heated under a controlled set of retort processing conditions. This is normally accomplished through the use of thermocouples inserted through the container wall so as to have the junction located at the slowest heating point. Thermocouple lead wires pass through a packing gland in the wall of the retort for connection to an appropriate data acquisition system in the case of a still cook retort. For agitating retorts, the thermocouple lead wires are connected to a rotating shaft for electrical signal pick up from the rotating armature outside the retort.

The precise temperature–time profile experienced by the product at the slowest heating point will depend on the physical and thermal properties of the product, size and shape of the container, and retort operating conditions. Therefore, it is imperative that test containers of product used in heat penetration tests be truly representative of the commercial product with respect to ingredient formulation, fill weight, headspace, can size, and so on, and that the laboratory or pilot plant retort being used is capable of accurately simulating the operating conditions that will be experienced during commercial processing on the production-scale retort systems intended for the product. If this is not possible, heat penetration tests should be carried out using the actual production retort during scheduled breaks in production operations. [*See* FOOD PROCESS ENGINEERING: HEAT AND MASS TRANSFER.]

E. Process Calculations

Numerical integration of Eq. (3) is the most versatile method of process calculation because it is universally applicable to essentially any type of thermal processing situation. It makes direct use of the product temperature history at the slowest heating point of the container obtained from a heat penetration test or predicted by a computer model for calculating the process sterilizing value delivered by a given temperature–time history.

In fact, this method is particularly useful in taking maximum advantage of computer-based data logging systems used in connection with heat penetration tests. Such systems are capable of reading temperature signals received directly from thermocouples monitoring both retort and product center temperature, and processing these signals through the computer. Both retort temperature and product center temperature are plotted against time without any data transformation. This allows the operator to see what has actually happened throughout the duration of the process test. As the data are being read by the computer, additional programming instructions call for calculation of the incremental process sterilizing value at each time interval between temperature readings and summing these over time as the process is under way (numerical integration of Eq. (3)). As a result, the accumulated sterilizing F value is known at any time during the process and can be plotted on the graph along with the temperature histories to show the final value reached at the end of the process. An example of the computer printout from such a heat penetration test is shown in Fig. 7.

III. New Developments

Thermal processing has been in use as a predominant method of food preservation since the middle of the

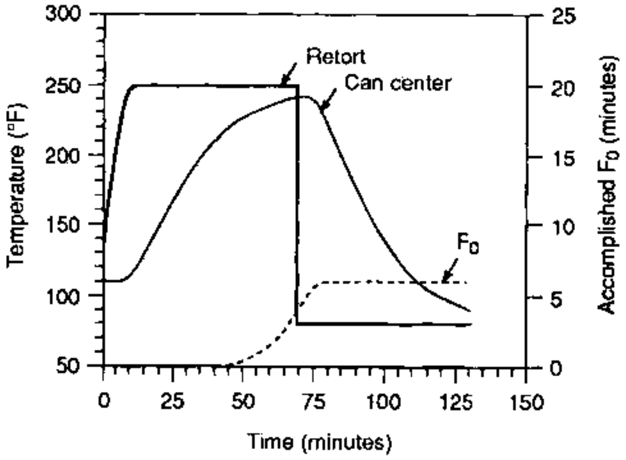

FIGURE 7 Computer-generated plot of measured retort temperature and calculated center temperature and accomplished F_0 for a given thermal process. [Reprinted with permission from Teixeira, A. (1992). Thermal process calculations. *In* "Food Engineering Handbook" (Heldman and Lund, eds.), Chapt. 11, Fig. 16, p. 585. Copyright © 1992 by Marcel Dekker, Inc., New York.]

19th century. Thus, people throughout the world have become quite familiar with canned foods packed in traditional metal cans and glass jars. Perhaps less apparent is the important role that this technology has had and continues to have in promoting and sustaining the health and well-being of populations throughout the world. Although the major portion of canned foods produced throughout history has been used to help feed the consuming public, this technology has also played a very strategic role in major world events. The famous "C"-rations which supported military troops through the first and second world wars were canned food rations. These rations remained safe and wholesome for consumption after long periods of storage and handling under highly stressful and abusive conditions.

Developments in new packaging materials and retort systems have brought about a host of innovative new canned food products that are often not recognized as being canned foods. By the end of the 20th century for example, most canned food rations for the military consisted of flexible retort pouches for use by infantry in combat because of their convenience, comfort (soft), and light weight when being carried on maneuvers. For feeding large numbers of military troops in field kitchens, canned foods came as fully prepared meals in large institutional-size rectangular steam-table trays ready to heat and serve by the kitchen staff.

Back on the home front, the increasing popularity of the microwave oven demanded canned foods in microwavable containers that were ready to "pop and zap." This has led to the increasing success of complete prepared meals in convenient microwavable lunch bowls or dinner trays that can be placed directly in the microwave oven and then taken directly to the dinner table as an attractive serving dish. Such products are hardly recognizable as traditional canned foods, but they are.

Perhaps least recognizable, however, is the important use that thermal processing technology has played in the pharmaceutical and health care industry. Large quantities and varieties of sterile solutions are required daily in various surgical and patient care procedures. Sterile saline solutions, irrigation solutions, intravenous solutions with dextrose or glucose, and dialysate solutions, along with a host of other large-volume parenteral solutions in glass, plastic, flexible, and semi-rigid containers are sterilized in retort systems using the technology of canning for food preservation. Such products, of course, are not thought of nor considered to be canned foods, but in fact represent a very important use of thermal processing technology throughout the world.

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Tillage Systems

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Glossary

Aggregate (soil) Unit of soil structure composed of many individual soil particles, usually formed by natural processes rather than by artificial processes, and usually less than 10 mm in diameter

Arable land Land so located that production of cultivated crops is economical and practical

Clean tillage Process of plowing and cultivation that incorporates all crop residues with soil and prevents the growth of all plants, except those of the crop being grown

Conservation tillage Any tillage system for which the object is to conserve soil and water. In practice, it is any tillage or tillage and planting system that results in at least 30% of the surface being covered with crop residues to control erosion by water after a crop is planted. To control erosion by wind, crop residues equivalent to at least 1.1 Mg/ha of small grain residues must be retained on the soil surface

Conventional tillage Tillage operations normally performed in preparing a seedbed for a given crop in a given geographical area

Erosion Detachment and movement of soil or rock by water, wind, ice, or gravity. For soil erosion on land used for crop production, water and wind are the prime erosive agents

No-tillage Procedure whereby a crop is planted directly into a soil with no preparatory tillage since harvest of the previous crop; usually, a special planter is used to prepare a narrow, shallow seedbed immediately surrounding the seed being planted

Seedbed Soil zone into which seed is planted

Tillage is defined as the manipulation, generally mechanical, of soil for any purpose, but, in agriculture, it is usually restricted to modifying the condition of the upper soil layers for crop production. Hence, a *tillage system* is the combination of tillage operations that is employed to modify the soil conditions for crop production in a given situation.

Since ancient times, farmers have sought ways to improve soil conditions for the crops that provided food and fiber for themselves and feed for their livestock. Early farmers used sticks to scratch the soil so that seeds could be covered, thus providing better conditions for seed germination and seedling establishment than that which occurred when the seeds were strewn on the soil surface. Even today, farmers in parts of the world still use sticks to punch holes in soil to plant their seeds. In other cases, the hoe is the common tillage implement of the farmer.

In developed countries, soil manipulation for crop production has become a highly mechanized and sophisticated process. A large array of tillage equipment has been developed to manipulate soils in an attempt to provide improved conditions for crops. For many years and in many cases, intensification of tillage to achieve the "ideal" soil condition was attempted. Within the last few decades, however, equipment, labor, energy, and other crop production costs have greatly increased. In addition, alternate pest (weed, insect, and disease) control practices have been developed. As a result, critical assessments have been made regarding the amount of tillage required to achieve satisfactory crop yields under a wide range of conditions. This has led to the use of less intensive tillage systems in many situations. Increased concern regarding the environment has accentuated the need to carefully assess the intensities and types of tillage systems used for producing crops because intensive tillage often results in increased soil erosion by wind and water.

I. Types of Tillage Systems and Equipment

A. Clean (Conventional) Tillage

Conventional tillage systems are those sequences of operations normally performed for the production of a given crop grown in a given geographical area. Certainly, what may be "conventional" in one area may not be so in another. Also, system designation as "conventional" changes with development and adoption of new practices. However, under current usage, conventional tillage is clean tillage in most situations, and that designation will be adhered to in this report.

By definition, clean tillage (or clean culture, clean cultivation) is the process of plowing and cultivation that incorporates all crop residues and prevents growth of all plants, except the particular crop being grown. The residues usually are covered by inversion-type tillage early in the interval between crops. In some systems, however, the first operation (as with disking) may only partially mix the residues with soil, then further mix them with subsequent tillage so that little or no residues remain on the surface when the next crop is planted. Unwanted vegetation between crops is controlled by various tillage operations (plow, disk, sweep, chisel, rod-weeder, etc.). Weeds during the crops' growing season are controlled by cultivation, hoeing, or herbicides. Although the value of plowing has been questioned for many years, clean cultivation is still widely practiced under many conditions. Only with the introduction of conservation tillage systems within the last 30 to 40 years has a trend toward less plowing developed.

B. Conservation Tillage

A widely accepted definition of conservation tillage is any tillage sequence that results in at least 30% of the soil surface being covered with crop residues after the next crop is planted to control water erosion. To control wind erosion, crop residues equivalent to at least 1.1 Mg/ha of small grain residues must be present during the major wind erosion period. However, more residues may be needed to effectively control erosion under some conditions and less under others. Stubble mulch tillage, reduced tillage, and no-tillage are types of conservation tillage.

1. Stubble Mulch Tillage

Stubble mulch tillage was developed primarily to help control wind erosion that was rampant in the U.S. Great Plains during the major drought of the 1930s. The value of this practice for also controlling water erosion and for conserving water was soon recognized. Hence, the stubble mulch tillage system is now widely used as a year-round system of managing crop residues for effective erosion control while, at the same time, controlling weeds and conserving water.

Stubble mulch tillage is accomplished with sweeps or blades that undercut the soil surface to sever weed roots and prepare a seedbed while yet retaining adequate residues on the soil surface to control erosion. Water conservation benefits are derived from controlling weeds that could use soil water, from surface residues that enhance water infiltration and suppress water evaporation, and, in some cases, from disrupting soil surface crusts, which could reduce water infiltration.

In general, stubble mulch tillage is better adapted to semi-arid or arid regions than to subhumid or humid regions, based on yields reported for crops in different regions. Possible reasons for good responses to stubble mulch tillage in the drier regions include lower nitrification in soil, which prevents overstimulation of plant growth and, in combination with greater water infiltration, improves the water-nutrient balance for crops. Better weed control possibly is another factor because weeds may not die if rain occurs soon after stubble mulch tillage. Because rain probability is lower in dry regions, weed control should be better.

2. Reduced Tillage

Controlling weeds is a major reason for tillage. Therefore, if weeds can be controlled by other means, the need for tillage is reduced, and one such means is the use of herbicides. In recent years, a wide array of herbicides has been developed for controlling weeds in many crops, which has resulted in the development of various reduced or minimum tillage systems. In these systems, herbicides usually are relied upon to control weeds during at least a part of the crop production cycle. However, in contrast to no-tillage, the entire soil surface is disturbed one or more times by tillage for seedbed preparation or crop planting. The reduction in tillage may be in intensity or in frequency of the operation. Some examples of reduced tillage systems that may still meet the surface residue amounts required for conservation tillage are:

1. *Fall (autumn) chisel, field cultivate.* Chiseling loosens a soil, but retains most residues on the surface. Field cultivating undercuts the surface, thus also retaining residues on the surface.
2. *Disk and plant.* Disking incorporates about 50% of surface residues at each operation. Hence, disking can retain adequate residues on the surface, if used sparingly and if adequate amounts are present initially.
3. *Till-plant.* Tillage with sweeps or blades that undercut the surface at the time of planting can retain sufficient residues on the surface to control erosion. By delaying tillage until planting, the surface can remain fully covered with residues during most of the year.
4. *Strip tillage.* Only a narrow band of soil is tilled in a strip tillage system, often with a rotary tiller. By attaching a suitable planter, tillage and planting can be achieved in one operation. Residues remaining on the surface between the tilled strips provide continuing protection against erosion.
5. *Herbicide-tillage combinations.* For these systems, herbicides are relied upon to control weeds, at least during a part of the crop production cycle. In general, tillage is performed as needed to control troublesome weeds, to loosen the soil, and to produce a seedbed. In some situations, tillage is performed to reduce surface residue amounts or to shift surface residues to improve conditions in the row zone for crop planting. The latter may also be used to hasten soil warming in the zone where the crop is planted. [*See* HERBICIDES AND HERBICIDE RESISTANCE; WEED SCIENCE.]

3. No-Tillage

With the no-tillage system, crops are planted directly into the soil with no preparatory tillage since harvest of the previous crop. The planting usually is accomplished by special planters that open a narrow slot or punch a hole in the soil for seed placement at the desired depth. The crops usually are not cultivated and weeds are controlled with herbicides. No-tillage is synonymous with no-till, zero-tillage, slot planting, ecofallow, sod planting, chemical fallow, and direct drilling, which are terms frequently found in the literature.

All crop residues are retained on the soil surface with a no-tillage system. Hence, no-tillage is widely recognized and is being promoted for its erosion-control benefits. When adequate amounts of residues are present, they help control water erosion in three ways. First, they protect soil surfaces from the bombarding action of falling raindrops, which can dislodge soil particles from the soil mass and render them subject to subsequent removal from the land by flowing water. Second, residues help maintain favorable water infiltration rates, which results in less water flow across the surface to transport dislodged soil particles from the land. Third, surface residues retard the rate of water flow across the surface, thus providing more time for some of the water to infiltrate into the soil and more time for soil particles to settle from the water before they can be transported from the land. For wind erosion control, surface residues, when adequate amounts are present, reduce the wind at the soil surface to nonerosive velocities.

Besides the erosion-control benefits, other advantages ascribed to no-tillage systems as compared with clean tillage or even other conservation tillage systems include improved water conservation (greater water infiltration and reduced evaporation), increased use of land, equal or greater crop yields, reduced energy requirements, reduced labor requirements, reduced equipment inventories, reduced wear and tear on farm equipment (tractors, plows, etc.), and greater net returns to the farming enterprise. The no-tillage system generally is well-suited for use on well-drained and moderately well-drained soils.

Results with no-tillage often are poor on poorly drained soils and where weeds are difficult to control with herbicides. Other disadvantages of the no-tillage system, at least under some conditions, include delayed planting due to lower soil temperatures in cool climates, increased use of chemicals, shift in weed populations, carry-over effect of herbicides, adverse effects of herbicides on adjacent crops, high cost of herbicides, greater pest problems (insect, disease, rodent), lack of adequate residues, greater soil compaction, and a need for a greater level of management by the farm operator.

Major improvements in planting equipment for no-tillage crop production have been made in recent years. Thus, most crops can now be planted by the no-tillage method. Improved sprayers have been developed also, which, along with improved herbicides, permit effective weed control in most cases. There is, however, concern about the greater use of chemicals in no-tillage systems with respect to the environment, especially with respect to water quality. Some chemicals (herbicides) readily move with water, thus contamination of both surface and groundwater is possible. Other chemicals are adsorbed on soil particles and are lost from fields when erosion occurs. Surface water contamination should be lower with no-tillage because it usually reduces runoff (increases infiltration). The increased infiltration, however, may cause water containing soluble chemicals to move deeper into the soil, thus possibly contaminating underground water supplies. To minimize surface and underground water contamination, all chemicals (herbicides, insecticides, fertilizers) must be applied at recommended rates and times, and according to established practices.

C. Ridge Tillage

Ridge tillage is a method of land preparation for crop production that involves deliberately raising the seedbed level above that of the surrounding soil. Reasons for using ridge tillage include improving drainage in the seed zone, allowing improved management of crop residues in a tillage system, and providing for improved soil conditions through cycling of crop residues in the plant root zone. To initiate a ridge-tillage system, ridges are built at the last cultivation of the previous crop or as soon as possible after harvest of that crop. The ridges are built from soil derived from the areas between the crop rows. Before planting the next crop, standing residues may be shredded, thus moving some residues into the furrows. At planting, a one-pass operation scrapes the ridge tops to move remaining residues into the furrows and to expose moist soil into which seed is planted. The ridges are built again at the last cultivation, which begins the next cycle.

Ridge tillage generally is better than no-tillage on poorly drained soils because it provides for improved aeration of the plant root zone. Other advantages of ridge tillage include early soil warm-up, thus allowing more timely crop establishment; good erosion control due to residues remaining on the surface for a major portion of the year; more timely planting than where more intensive tillage systems are used (under wet soil conditions, planting can be accomplished instead of first plowing to prepare a seedbed); lower costs than where more intensive tillage methods are used; and the potential for reduced soil compaction because wheel-track traffic can be confined to certain furrows.

II. Goals of Tillage

A. Overall Goals

The overall goals of tillage are (1) to create soil conditions that will result in crop growth and yields at a satisfactory level, (2) to help protect the environment, and (3) to protect soil resources so that an adequate amount of arable land will be available to future generations on which to grow their food, fiber, and feed crops. The first of these goals usually is of primary concern for producers, and may be of major concern also for policy makers and society as a whole. The producers' goals regarding tillage center around crop production at a satisfactory level to provide the required products for sale and possibly for the families' food and fiber needs as well as feed for livestock. The tillage system employed must result in production at a level that will provide favorable returns to producers' investments so that long-term economic viability can be achieved. Certainly, many producers are concerned also about the environment as well as maintaining the productivity of the land for future generations.

Concern about the environment has increased greatly in recent years, and will increase in the future. Tillage systems employed may affect the water, air, and esthetic quality of the environment. Hence, to meet the environmental standards that regulatory agencies and society as a whole have set or expect, tillage systems are being closely scrutinized regarding their affect on the environment.

The world's area of arable land is finite. All arable land at present is not available for crop production and additional amounts are being constantly removed from cultivation for such purposes as transportation (highways and airports), commercial ventures (factories, businesses, and warehouses), parks, and residential areas. Will there be enough arable land on which future generations can grow their food, fiber, and feed crops? For the near future, adequate amounts are available. However, the productivity of the land must be preserved because the world's human population continues to increase rapidly, which is causing increased demands for food and fiber. Even at present, arable land is severely limited in some regions of the world, which is contributing to famine in some countries. Tillage systems employed may enhance, maintain, or decrease soil productivity. They also may result in soil degradation, which may render them unsuitable for crop production in the future. Therefore, careful selection and evaluation of tillage systems are essential for maintaining the long-term productivity of soils suitable for crop production.

B. Specific Goals

Specific goals for tillage are varied and numerous, and many of them complement one another. The goals include seedbed preparation, weed control, water conservation, erosion control, plant residue incorporation (when excessive amounts are present), fertilizer and pesticide incorporation, soil aeration improvement, irrigation land preparation, insect habitat destruction, and plant rooting depth improvement.

1. Seedbed Preparation

Successful crop production is greatly dependent upon successful seed germination and seedling establishment, which rely on beginning the crop growth cycle with a well-prepared seedbed. In a well-prepared seedbed, viable (live) seeds readily absorb water when placed and firmed in contact with moist soil. A well-prepared seedbed also provides for adequate aeration and soil temperatures for timely seed germination and seedling emergence and establishment. Tillage is widely used for seedbed preparation, but no-tillage crop production systems are gaining acceptance for some crops.

The crop to be grown has a major influence on the type of seedbed required. Crops having small-size and high-cost seed, for example, some vegetables, grasses, alfalfa, and clovers, require a seedbed of relatively small soil aggregates to assure uniform planting depth and adequate seed–soil contact. In contrast, larger-seeded crops, for example, corn, soybean, small grains, sorghum, dry bean, and cotton, do not require a seedbed primarily composed of small aggregates. The implement used and the depth and speed of its operation strongly influence the size distribution of aggregates resulting from a tillage operation on a given soil. Soil water content at the time of tillage also influences aggregate size distribution. Implements that invert the plow layer (moldboard and disk plows) often result in a rough soil condition that requires additional tillage with a disk or harrow to achieve a satisfactory seedbed. Even so, the resultant seedbed may not be as fine as that achieved by use of implements (disk harrows and rotary tillers) that mix the upper soil layers. Rotary tillage is especially suited for obtaining a good seedbed for small-seeded crops.

2. Weed Control

Weed control is essential for successful crop production because weeds compete with crop plants for water, light, nutrients, and space. Until the development of herbicides, a primary reason for tillage was to control weeds. Although tillage operations often achieved both weed control and seedbed preparation, fewer tillage operations would have been necessary if weeds were not a problem or if they were controlled by other means. Such control became possible when herbicides were developed to control weeds in many crops. At present, tillage is still used in many cases, but proper use of appropriate herbicides often makes tillage unnecessary for weed control.

3. Water Conservation

All crop plants require water, but competition for water is increasing among agricultural, residential, industrial, and recreational users. Hence, water conservation is of prime interest where water supplies for agriculture are limited because water deficiencies can greatly reduce crop yields. While deficiencies seemingly are more common, excess water also is detrimental to crop production under some conditions. Tillage systems can be used to conserve water on or remove excess water from cropland, depending on such factors as crop row orientation relative to soil slope, surface roughness resulting from tillage, amount of crop residues remaining on the surface after tillage, presence of soil surface crusts, and degree of disruption by tillage of soil layers that impede water movement. In general, water conservation is improved by row orientation across the slope (contour tillage), increased surface roughness, increased surface residues, and reduced surface crusting, either through greater water infiltration or by reduced soil water evaporation. Water removal from land is enhanced by row orientation with the slope (up and down the slope), smooth soil surfaces, low surface residue amounts, and crusted surfaces. Disruption of impeding layers can enhance water conservation by allowing more water to infiltrate a soil, but it can also enhance water removal by allowing drainage to depths beyond the reach of plants, thus avoiding possible harmful affects of excess water. [*See* SOIL AND WATER MANAGEMENT AND CONSERVATION.]

4. Erosion Control

The tillage system used strongly influences the potential for soil erosion, both by water and by wind. Whereas clean tillage often results in highly erodible soil conditions, conservation tillage systems are widely recognized for their erosion control benefits because they are designed to retain crop residues on the soil surface.

Water erosion control under conditions where surface residues are not used can be achieved by tillage that helps retain water on the land. The same practices that help conserve water (see Section III.B.3) also help control erosion by water because, if water is retained on the land, it cannot transport soil particles from the land.

For wind erosion control, surface residues, when adequate amounts are present, reduce the wind at the soil surface to nonerosive velocities. Where residues are not available or present in adequate amounts, wind erosion control can be enhanced by using tillage practices that result in a rough, cloddy surface; bring nonerodible soil aggregates to the surface and bury erodible soil materials; or provide ridges perpendicular to the direction of prevailing winds.

5. Plant Residue Incorporation

With irrigation and in high-precipitation regions, crops may produce more residues than needed for controlling erosion and amounts that interfere with tillage, pest control, planting, and other crop production operations. They also may adversely affect seedling growth and, consequently, crop yields. Large amounts of residue are of concern mainly where annual cropping and double cropping (more than one crop grown annually) are practiced because of the relatively short time between harvest of one crop and planting of the next crop. Although equipment is available for planting crops under high-residue conditions, it may be desirable to incorporate some of the residues, and various types of tillage equipment are available for this purpose. Any tillage operation results in some residue incorporation. Moldboard and disk plows result in the greatest, disks in intermediate, and sweep or blade plows in the least amounts of residue incorporation. Careful selection of tillage system is essential for assuring that adequate residues will be retained on the land for erosion control where residues are relied upon to help control erosion.

6. Fertilizer and Pesticide Incorporation

Fertilizers that move readily with water such as some nitrogenous materials can be surface-applied and still effectively provide nutrients to crops, but anhydrous ammonia, a gaseous form of nitrogen fertilizer, must be placed in soil to avoid significant losses. Anhydrous ammonia is injected into soils under pressure, usually through chisel point openers. Such openers help loosen a soil, but do not invert the surface or have a major effect on surface residues. In contrast, other fertilizers such as phosphorus materials usually must be incorporated with soil either in narrow bands or over the entire field to be effective. Where lime is needed to alleviate acid-soil conditions (low soil pH), it usually also must be incorporated to be effective. Phosphate fertilizers and lime can be incorporated with a variety of tillage implements. Depending on the method used and the resultant degree of residue incorporation, remaining amounts of residues may be inadequate to achieve effective erosion control. [*See* FERTILIZER MANAGEMENT AND TECHNOLOGY.]

As for fertilizers, some pesticides are surface-applied, others must be incorporated. Incorporated pesticides for weed and insect control must be mixed uniformly across the entire field for maximum effectiveness. Greater effectiveness of pesticides is achieved with tillage implements such as disk harrows and rotary tillers that mix the soil than with implements that invert the soil (moldboard or disk plows) or only loosen the soil (chisels and sweep plows).

7. Soil Aeration Improvement

Proper air supplies in the plant root zone are essential for good plant growth. While a crop such as rice can grow in water, others must have good access to air (oxygen) that is supplied to plant roots through pores in the soil. Coarse-textured soils (sandy soils) usually have no aeration problems, but fine-textured soils (clay soils and some silty soils) have fine pores that restrict air movement and, hence, may cause poor aeration. Poor aeration can be overcome by tillage that loosens dense or compacted soil zones. However, if the soil initially is in good physical condition, good aeration can be maintained by use of conservation tillage, especially no-tillage, because it does not disturb the channels resulting from decayed plant roots, burrowing insects, and earthworms.

Poor aeration can also be overcome by performing tillage in a manner that results in drainage of excess water from the land. The drainage may occur as water flows across the surface in furrows or especially designed channels (terraces, waterways), or through an underground drainage system (pipes, tiles, etc., or a mole-drain system). The latter is installed by pulling a bullet-shaped cylinder through the soil, thus forming an unlined channel for water flow to a suitable outlet.

8. Irrigation Land Preparation

Land surface preparation is critical where flood or graded-furrow irrigation systems are used because the goal is to achieve uniform water application over the entire area. For flood irrigation, the entire surface is leveled, usually in basins that retain the applied water until it infiltrates into the soil. Special land-leveling equipment, often in conjunction with some type of clean tillage to loosen the soil, is used to level the land. [*See* IRRIGATION ENGINEERING: FARM PRACTICES, METHODS, AND SYSTEMS.]

Graded-furrow irrigation is practiced on land having slight, relatively uniform slopes. To improve uniformity in fields, some land planing (moving soil from high to low points in the field) may be required. Once the desired slopes have been established, ridge- and furrow-forming tillage (lister or disk-bedder) is performed. Then the water is applied to the land at the upslope end and allowed to flow downslope to irrigate the field. Land preparation for graded-furrow irrigation generally involves clean tillage.

In many cases, no special land preparation is used for sprinkler irrigation because center-pivot or lateral-move systems are capable of traversing land with uneven slopes. However, for systems that apply water at low pressure and at a relatively high rate, special small depressions are often needed on the land surface to minimize or prevent water losses by runoff. Construction of these depressions is accomplished by using tillage to form ridges and furrows along the direction of travel of the sprinkler system, then diking the furrows at short distances (about 3 m) with special furrow-diking equipment. With properly designed systems, greater than 95% efficiencies of irrigation water applications have been achieved.

9. Insect Habitat Destruction

Certain insects survive from one crop to the next in crop residues. Thus, plowing under of crop residues has long been promoted as an effective means of controlling such insects. Insects controlled or at least kept in check by plowing under crop residues include the Hessian fly for wheat, wheat jointworm, European corn borer, grasshoppers, and cotton boll weevil and pink bollworm. In general, clean tillage is more effective than conservation tillage for destroying insect habitats. Where surface residue retention is essential for other purposes (for example, erosion control and water conservation), effective insect control in some cases can be achieved by crop rotations or by timely applications of insecticides.

10. Plant Rooting Depth Improvement

Plants depend on the water and nutrients stored in soil to sustain them between precipitation or irrigation events or nutrient applications. When plant root growth is restricted by dense, impervious layers in the soil, the water and nutrients available to plants may not be adequate to provide for the desired level of plant growth. Hence, deeper loosening of such soil could result in more water and nutrients being available to the plants.

Tillage can be used to alleviate such naturally occurring or traffic-induced (farming equipment or animal) zones, provided they are sufficiently near the surface to be reached by the tillage implement. A variety of implements (plows, disks, chisels, sweeps, subsoilers, etc.) are available for soil loosening. The implement selected should be capable of reaching and effectively loosening the restrictive zone. Common implements (plows, sweeps, chisels, etc.) usually are limited to the upper 0.20 to 0.30 m of a soil. Deeper loosening is possible with special subsoilers. Under some conditions, soils have been loosened to depths of 1.50 m with special equipment.

III. Effectiveness of Different Systems for Attaining the Goals

A. Clean Tillage

The overall and specific goals of tillage discussed above can be attained through proper use of clean tillage under most crop production conditions. Exceptions are on highly erodible soils where clean tillage usually results in major soil losses by water or wind, even under normal rainstorm or wind conditions. During major rainstorms or windstorms, devastating soil losses may occur under some conditions where clean tillage is used. Clean tillage may also result in less-than-desirable water conservation where water infiltration is low, as on sloping soils and unstable soils for which a surface seal develops during water (rainfall or irrigation) application, and where water losses by evaporation are high. Evaporation is greater from bare (clean tilled) than from residue-covered soils under most conditions.

B. Conservation Tillage

The overall and specific goals for tillage can be attained by using some type of conservation tillage under most crop production conditions. Stubble mulch and reduced tillage generally are as effective as clean tillage for most goals, but usually result in more effective soil and water conservation than clean tillage. Plant residue incorporation is not a goal with stubble mulch or reduced tillage. Rather surface residue retention usually is the goal and an advantage of using these systems. Insect habitat destruction may be less than desirable with stubble mulch or reduced tillage than with clean tillage under some conditions. To prepare land for irrigation, as by surface leveling, a residue-free surface usually is needed to achieve uniform and trouble-free operation of the equipment. Therefore, stubble mulch and reduced tillage would not be satisfactory in most cases.

Good crop production is achieved by using no-tillage in many cases, which suggests that this system is effective for attaining the goals for tillage. Certainly, the no-tillage system is highly effective for controlling erosion and conserving water under many conditions because of the greater amounts of crop residues retained on the soil surface. However, just as certainly, residues, fertilizers, and pesticides cannot be incorporated; land cannot be prepared for irrigation; insect habitats cannot be destroyed; and plant rooting depth cannot be mechanically increased where a no-tillage system is used. Where these goals are essential, they must be performed before converting to a no-tillage system.

No-tillage is not adaptable to soils in a degraded condition, and such condition must be corrected before using no-tillage. However, no-tillage is capable of improving a soil by (1) reducing erosion, (2) improving water conservation for improved crop production and, hence, more residue production for further improvements in soil and water conservation, (3) increasing plant rooting depth by not disturbing channels in soil that result from plant root decay, earthworms, and insects, and (4) promoting microbiological activity in soils, which can result in improved soil physical condition and, hence, an improved seedbed for crop establishment. Overall, no-tillage is the cropping system most capable of sustaining the long-term productivity of soils under most conditions.

C. Ridge Tillage

As for clean and conservation tillage, the overall and specific goals can be attained by using ridge tillage under most conditions. An exception is land preparation for irrigation, especially where land surface shaping (for example, leveling) is needed. Where such operation is needed, it must be performed before adopting a ridge tillage system.

In general, erosion control and water conservation should be better with ridge tillage than with clean tillage, but possibly not as good as with conservation tillage, especially with no-tillage. No-tillage provides for continuous surface protection by residues, even after crop planting. In contrast, some bare soil is exposed at planting where ridge tillage is used, and this could result in erosion by water or wind as well as less water infiltration and greater evaporation under some conditions. Clean tillage results in bare surfaces for prolonged periods, which renders soils subject to erosion and water losses until a crop becomes well established, unless the tillage system used results in surface conditions that minimize or prevent soil and water losses.

IV. Summary

Farmers have sought ways to improve soil conditions for crop production since ancient times. While primitive implements are still used in some countries, soil manipulation for crop production has become a highly mechanized and sophisticated process in developed countries. Many tillage implements have been developed to manipulate soils in an attempt to improve conditions for crops.

Tillage intensification to achieve the "ideal" soil condition was common in many cases for many years. In recent decades, however, alternate practices for controlling pests (weeds, insects, diseases), long a major reason for tillage, have been developed. Such practices along with increased concern for the environment and increasing production costs have resulted in critical assessments regarding the amount of tillage needed to achieve satisfactory crop production under many conditions. As a result, clean tillage, usually an intensive form of tillage that results in crop residue incorporation with soil, is being replaced in many cases by less intensive forms of tillage, for example, conservation and ridge tillage, that result in crop residue management on the soil surface.

The overall goals of tillage are to achieve satisfactory crop production, help protect the environment, and preserve the soil resources for use by future generations. Specific goals for tillage include seedbed preparation, weed control, water conservation, erosion control, residue incorporation, fertilizer and pesticide incorporation, soil aeration improvement, irrigation land preparation, insect habitat destruction, and plant rooting depth improvement. These overall and specific goals can be attained by proper use of any of the various tillage systems in most cases. However, the degree of attainment varies with the system used; other goals are not attainable with some systems.

In general, erosion control and water conservation are greater with conservation tillage, especially no-tillage, than with clean tillage; ridge tillage gives intermediate results. Because conservation and ridge tillage involve crop residue management on the soil surface, major operations such as land leveling to prepare land for irrigation must be done before these tillage systems are adopted. Also, fertilizer and pesticide incorporation and deeply loosening a soil mechanically are not possible with no-tillage in most cases, but they can be accomplished with a reduced tillage system.

Tillage systems will continue to be used to obtain desirable conditions for satisfactory crop production. A variety of systems are available, and the system selected should be used properly so that the overall and specific goals for tillage can be attained.

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Tobacco

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Glossary

Burley tobacco Stalk-cut, air-cured tobacco type; cured leaves are reddish-brown in color, with lighter body, greater absorbency and filling power, lower sugar content, and higher alkaloid content than other types

Fire-cured tobacco Stalk-cut tobacco that is cured in widely ventilated barns with open fires under the tobacco; the fires produce smoke that is allowed to contact the tobacco and is the only source of artificial heat; cured leaves of fire-cured tobacco are light to dark brown in color with moderate to heavy body and strong flavor

Flue-cured tobacco Tobacco that is sequentially harvested as leaves ripen; flue-cured tobacco leaves are cured according to a precise schedule of heat and moisture control; leaves are lemon to orange-yellow in color, with a sweet aroma and a slightly acidic taste, and with a relatively high sugar content and relatively low alkaloid content

Layby Final cultivation of a tobacco crop in which soil from the middle of the row is thrown up against the tobacco to form a large bed, which is needed for good root system development for nutrient uptake and to help keep mature tobacco plants upright

Nicotine Most abundant alkaloid in tobacco and one of the primary leaf constituents desired in tobacco products; nicotine content is generally balanced with carbohydrate and sugar levels within cured tobacco leaves

Order Condition of cured tobacco leaves in which their moisture content is high enough so that leaves are soft and malleable, but not so high as to be predisposed to molds and rots; also referred to as "condition" or "case"

Oriental tobacco Class of tobacco traditionally grown in Greece and Turkey; oriental tobacco is commonly primed and air-cured to produce lemon-colored leaf that possesses a characteristic flavor; cured oriental leaf has a relatively high sugar content and a relatively low alkaloid content, with many nonvolatile acids and volatile flavor oils

Priming Removal of tobacco leaves from the stalk, traditionally performed by hand; leaves are generally harvested from the stalk as they ripen, so that bottom leaves (often called "primings") are removed first and top leaves last; in flue-cured tobacco (the predominant tobacco type harvested by priming) approximately three to five leaves are removed at each harvest, "priming," or "pulling"

Stalk-cut tobacco Tobacco types that are harvested by cutting the entire plant or stalk, and are usually air- or fire-cured; burley tobacco is the predominant stalk-cut tobacco type

Tobacco *Nicotiana tabacum*, a solanaceous plant species cultivated for its leaves, which are smoked or chewed for their content of nicotine

Topping Removal of the apical inflorescence, usually along with several small tip leaves; most tobacco types are "topped" at or near the onset of flowering to increase the size, thickness, body, and nicotine content of leaves

Tobacco is a solanaceous plant whose leaves are harvested, cured, and smoked. Although Christopher Columbus was the first European to record the use of tobacco, native Americans and, possibly, the Chinese had been cultivating and smoking tobacco for centuries before. Since Columbus' time, tobacco culture has spread throughout the world. Tobacco seedlings are generally grown in outdoor plant beds before being transplanted in fields. Tobacco fields are fertilized with nitrogen, phosphorus, and potassium at or before transplanting. The crop grows slowly during the first month of the growing season when fields are cultivated. Once cultivation has been completed, the crop grows very quickly and must be protected from a number of pests and diseases during the growing season. Growth of undesired lateral shoots must also be controlled after removal of apical inflorescences. Some types of tobacco, such as burley, are harvested by cutting the entire plant from the roots. Other types, particularly flue-cured tobacco, are harvested by sequentially removing leaves from the stalk. The tobacco curing process manages the moisture content and temperature of tobacco leaves to obtain the desired levels of nicotine and reducing sugars within the leaf. Different tobacco products require varying levels of these constituents. New uses for tobacco are currently being explored. New technologies manipulate tobacco physiology to produce industrial chemicals, food supplements, antibiotics, and enzymes.

I. Classification, Origin, and History of Tobacco

The word "tobacco" generally refers to *Nicotiana tabacum*, although *Nicotiana rustica* is used for similar purposes in some parts of the world. The word tobacco is of Spanish origin. It may have arisen from the name of Y-shaped tubes or pipes used by native Americans for smoking, from the Tabasco province of Mexico, or from the West Indian island of Tobago. The genus name *Nicotiana* and the term nicotine were derived from the name of the French ambassador to Portugal, Jean Nicot, who introduced tobacco to France in 1560. The genus *Nicotiana* is in the family *Solanaceae* and contains 3 subgenera, 14 sections, and 64 species. *Nicotiana* is primarily a New World genus, but 15 species are native to Australia. *Nicotiana tabacum* is a perennial allotetraploid with 24 chromosomes. Although *N. tabacum* probably originated from a natural hybridization of *N. sylvestris* and *N. tomentosiformis* in Brazil or Central America, it has never been found in the wild state.

Native Americans cultivated *N. tabacum* throughout the Western Hemisphere in pre-Columbian times. The Chinese may also have grown and used tobacco long before Columbus landed in the Bahamas in 1492. Although *Nicotiana* species are not native to the eastern part of North America, native Americans cultivated and used *N. rustica*. European explorers observed native Americans chewing and sniffing tobacco, as well as smoking it in pipes, rolling it into cigars, and pouring it into "cigarettes" made from palm leaves.

Tobacco use spread rapidly through the world following Columbus' voyages, mostly smoked in cigarlike forms or in pipes. Tobacco culture spread to Europe, Asia, and Africa during the last half of the sixteenth century. The first confirmed reference to a cigarette was made in 1518 in Mexico, but modern cigarettes may have developed in Spain, where "papeletes" were used as early as 1635. Use of papeletes spread to France, where significant improvements were made, and where the product was first called a "cigarette." Cigarettes remained a minor form of tobacco use until late in the 1800s. Development of high-speed cigarette-making machines and the introduction of the "American blended cigarette" revolutionized the tobacco industry and dramatically increased demand for tobacco leaf.

Because manufacturers of tobacco products require specific leaf characteristics, they tend to be very concerned that specific producing areas continue to produce consistent quantities of the type of tobacco leaf that they need. Therefore, tobacco producers tend to enjoy a more stable demand, resulting in higher prices, for their product than that experienced for most other agricultural commodities. Most classes of tobacco are highly suited to coarse-textured soils of low inherent fertility, which are often also poorly suited for production of alternative crops. Tobacco production has tended to dominate areas where it has become established.

The United States Department of Agriculture classifies cultivated tobacco into 8 classes and 26 types, reflecting differences in plant genetics, curing methods, fertilization and management, and soil and weather characteristics of the geographic regions where each is produced (Table I). Cultivated tobacco is grown in most countries of the world. *Flue-cured tobacco* is the most widely grown tobacco type. The term "flue-cured" reflects the heating systems used in early curing barns, when hot air was transported into the barns via flues. Until around 1875, flue-cured tobacco was harvested by cutting the entire stalk, and thereafter the "priming" method of sequential harvest began. In the United States, it is produced from southern Virginia to north Florida. Major flue-cured tobacco-producing countries include Brazil, China, India, the United States, and Zimbabwe. Flue-cured

TABLE I
Characteristics of Different Tobacco Types

Class/type of tobacco	Soils	Nitrogen fertilization (kg/ha)	Leaves per plant	Harvest initiation (weeks after topping)	Harvest method	Curing method	Cured leaf color
Flue-cured	Sandy loams	56–112	18–24	2–10	Primed	Heat	Lemon to orange
Fire-cured	Silt loams	140–168	12–16	4–6	Stalk-cut	Heat + smoke	Light to dark brown
Light air-cured							
Burley	Silt loams	140–280	18–22	3–4	Stalk-cut	Air	Straw to brown
Maryland	Sandy loams	67	16–20	3–4	Stalk-cut	Air	Shades of brown
Dark air-cured	Silt loams	140–168	15–18	4–6	Stalk-cut	Air	Shades of brown
Cigar filler	Silt loams	56–112	12–16	2–3	Stalk-cut	Air	Dark brown
Cigar binder	Sandy/silt/clay loams	224	15–18	2–3	Stalk-cut	Air	Dark brown
Cigar wrapper	Sandy loams	168–235	15–30	N/A	Primed	Air	Light tan to gray brown
Perique	Sandy loams	140–168	12–14	3–4	Stalk-cut	Air, then fermented	Black
Oriental	Wide variety	0–224	24–30	N/A	Primed	Open air	Lemon to dark brown

tobacco is described as possessing full body and being rich in aroma and flavor. Fire-cured and air-cured tobaccos are *stalk-cut tobacco types*. In contrast to flue-cured tobacco, fire-cured and air-cured tobaccos are harvested by cutting the aboveground portion of the plant near ground level. Harvested plants are typically speared onto a wooden stick. Once the leaves have wilted, plants are placed in wooden curing barns. Leaves remain on the stalk during the curing process. The curing process does not involve any heating, but is controlled by adjustments in ventilation. Cured leaves are "stripped" from the stalk, separated into grades, and tied or baled for auction. Most *fire-cured tobacco* is grown in Virginia, Kentucky, and Tennessee. It has a distinctive aroma obtained by "smoking" leaves over open fires that burn hardwood, such as oak or hickory.

Burley tobacco, most cigar tobacco types, dark, air-cured, Maryland, and Virginia sun-cured tobacco types are all examples of *air-cured tobacco*. *Burley tobacco* originated from a genetic mutation discovered by Mr. George Webb of Higginsport in Brown County, Ohio, in 1864. Most of the burley tobacco grown in the United States is produced in Kentucky, Tennessee, Virginia, North Carolina, and Ohio. Much burley tobacco is also produced in Brazil, China, Italy, and Malawi. *Maryland tobacco* is grown on the light, sandy loam soils of southern Maryland, whereas the *dark air-cured tobacco* types are grown on heavy silt loams in Kentucky and Tennessee or on sandy loam soils with a heavy clay subsoil in Virginia. *Cigar tobaccos* are divided into three classes: cigar filler tobacco, cigar binder tobacco, and cigar wrapper tobacco. Shade-grown cigar wrapper tobacco is produced in fields enclosed by cloth tents. The artificial shade and protection from wind movement provided by the tents produce the thinner, longer, smoother, small-veined leaves that are needed to wrap cigars. Shade tents are constructed by erecting a wire frame supported by stout posts. Tents are usually 33 feet wide and 125 feet long.

Oriental tobacco is produced in Bulgaria, Greece, Turkey, and Yugoslavia. Leaves are much smaller than those produced by other tobacco types. Harvested leaves are gathered into bundles, sewn onto cotton twine, allowed to wilt in the shade for 24 hr, and then placed in racks or frames in direct sunlight. Curing structures must be covered each night to prevent formation of dew on the strung leaves. After curing, leaves are temporarily hung in garlands, but are sold in bales.

II. Commercial Production of Tobacco

A. Seedling Production

The commercial production of tobacco begins with the growing of seedlings to be transplanted to the field. Management of transplant production systems is particularly important because the grower is dependent on the availability of healthy transplants. Tobacco seed has traditionally been started in plant beds or seedbeds owing to the difficulty of direct-seeding in the field. The seed is relatively delicate and is very small (ca. 11,000 to 12,000 seeds per gram). The use of plant bed techniques provides the grower with the ability to control environmental conditions and thereby ensure favorable conditions for seed germination and seedling growth. The following practices for producing tobacco transplants are general procedures that hold for most types of tobacco produced in most areas of the world.

1. Site Selection

Plant beds should be located on deep, fertile, well-drained soils with good moisture-holding capacity. Plant bed sites with a southern or southeastern exposure and a windbreak on the northern or western sides will have the most favorable local weather conditions. Surface water drainage is very important; plant bed sites should have a gentle slope and may include drainage ditches, if necessary, to eliminate standing water in the beds. Permanent plant bed sites are often established, although rotation of individual plant beds within a permanent site is advisable. Plant beds should be located near a clean water source for irrigation and near the grower's home to make day-to-day management more convenient.

2. Soil and Fertility Management

A cover crop should be grown on plant beds between tobacco growing seasons to maintain the physical condition of the soil and to minimize weed growth. Tobacco plant beds can be constructed to any size, but are usually 2.7 to 4.6 m wide and of variable length. The size of a plant bed, particularly width, is generally determined by convenience in seeding and maintaining the area. All plant material or residue must be removed before seeding. This is often accomplished by disking plant bed areas in the fall and allowing several months for plant residue to decompose. Just prior to seeding, plant bed areas are moldboard-plowed or disked toward the center of the bed. This pattern of working the soil should leave the center of the bed slightly higher than the surrounding area. This "crowning" of the plant bed improves surface drainage, a common plant bed problem. After the plant beds have been plowed, the soil should be harrowed or raked until it is well-pulverized and smooth, and free of clods (important for adequate seed-to-soil contact and thus good germination). To reduce soil compaction, the use of tractors and other heavy equipment directly in the beds should be avoided following final tillage operations. Plant beds are fumigated, with methyl bromide or a similar fumigant to control soil-borne pathogens and weeds.

Plant beds are fertilized with "complete" or mixed fertilizers containing nitrogen, phosphorus, and potassium. Preplant fertilizers are worked into the soil to a depth of 5 cm. Although organic fertilizers have been used on tobacco plant beds, mineral fertilizers are now generally recommended. Nitrogen is normally the predominant ingredient in tobacco plant bed fertilizers, and though nitrogen fertilizers can have several forms, at least 35 to 50% of the nitrogen in a preplant plant bed fertilizer should be in the nitrate form, rather than as ammonium. Additional fertilizer applications are usually recommended only when nutrient deficiencies are encountered. The most common nutrient deficiencies involve nitrogen and sulfur. Nitrogen deficiencies can be corrected by applying a nitrate-nitrogen fertilizer. Sulfur deficiencies are usually corrected with sulfate of potash-magnesia or magnesium sulfate.

3. Seeding

Plant beds are usually seeded 60 to 65 days before a grower plans to transplant his or her crop. Plant beds have traditionally been seeded by hand. The seed is evenly broadcast over the bed by mixing a small quantity of seed with a much larger amount of an inert material (sand, lime, ashes, etc.) or fertilizer (nitrate of soda). Whatever the method, tobacco seed should be evenly scattered over the soil surface, rolled (with a water-filled drum), and lightly irrigated or rained upon to ensure good seed-to-soil contact. Beds are lightly covered with a layer mulch of straw, pine needles, or similar material to keep the seed moist and slightly raise the cover off of the small seedlings. Seeding rate, the number of seed per unit area, is a very important parameter because seedling density largely determines a number of very important characteristics of tobacco transplants. Beds are generally seeded at a rate of 1 ounce of seed to 600 to 800 square yards of plant bed. Beds that are too dense will result in tall, spindly transplants, whereas too few plants will result in short plants with large leaves. A desirable transplant has some stem elongation (12 to 15 cm), that is, a strong stem that is not woody and is the approximate diameter of a wooden pencil.

4. Moisture Management

Tobacco plant beds need to be watered whenever the soil begins to dry. Irrigation may be needed only intermittently in temperate regions such as the tobacco-growing areas of the United States. In drier areas of the world, however, more extensive irrigation is necessary. Soil type and the type of plant bed cover also influence how much and how often plant beds must be watered. Irrigation is needed more frequently with sandy soils and when more porous cover materials are used. Plant beds should be watered often, but lightly during the first 3 weeks after seeding. Plant beds should be irrigated with a greater quantity of water less frequently once seed have germinated. Plant beds should be irrigated slowly, so that water can be absorbed as it is applied.

5. Cover Management

Once the plant beds are seeded, they must be protected by covering with one of several types of material, generally manufactured of cotton, nylon, polyethylene plastic, or spun polyester. In some areas outside of the United States, plant beds may be covered with thatching grass, banana leaves, or a chopped grass mulch. Plant bed covers protect developing plants against cold and wind and help maintain soil moisture. Caution must be exercised when using plastic covers as they may produce excessively high temperatures if not managed properly. Growers using plastic covers perforate the cover, usually with a hand-drawn rolling punch, in order to provide additional cooling under the plastic covers. Covers should be removed when temperatures outside the plant bed reach 30°C for two consecutive days and replaced if nightly low temperatures fall to below 7°C.

6. Mechanization

Many U.S. tobacco producers are adopting a number of new production practices for tobacco plant beds, primarily to reduce the labor involved in raising tobacco transplants. Narrower, raised plant beds (1.2–1.8 m wide vs. 2.7 m wide) are being used to facilitate use of tractor-mounted field equipment to maintain the bed and to reduce surface water drainage problems. Mechanical or precision seeding using pelleted or coated seed is being used to more closely approach optimal plant populations within plant beds and to improve the seedling uniformity. "Clipping" or the removal of leaf tips extending above the terminal buds of seedlings has become a standard production practice for most growers in the United States. Regular clipping will increase transplant size and uniformity and may be used to delay transplanting if field conditions warrant. Lawn mowers and tractor-mounted rotary mowers are often used for clipping plant beds. The increased seedling uniformity made possible by these new practices allows growers to remove a larger percentage of the seedlings within a plant bed at any given time, thus increasing the efficiency of the transplanting operation. Further labor reductions can be obtained by "undercutting" plant beds, that is, by pulling a tractor-mounted metal blade through the soil just below seedling root systems.

7. Greenhouse Transplant Production

The use of greenhouse technology is a recent alternative to outdoor tobacco plant beds. Although Canadian growers have utilized greenhouse culture for many years, the practice has become common in the United States only since approximately 1989. Greenhouse technology provides the grower with more control of growing conditions, produces more uniform transplants, and eliminates hand labor associated with pulling transplants from a plant bed. The principal disadvantage is the capital investment in the structure, which is not generally used for the production of other crops or commodities. [*See* HORTICULTURAL GREENHOUSE ENGINEERING.]

Greenhouse systems used for tobacco transplant production differ primarily according to how the plants receive water. In an overhead-watered greenhouse, plastic trays are filled with soilless media and placed closely together on the greenhouse floor. Water is applied with an overhead irrigation system. Trays must be watered frequently during the day to ensure that the media is not allowed to dry. Nutrients are provided with water-soluble fertilizers applied in the irrigation water. Growth of the seedlings may be regulated by the amount and frequency of water and fertilizer application. Overhead-watered greenhouses are direct-seeded using specially coated seed that may be placed individually into each cell of the trays. Generally 1175 plants per square meter are grown in overhead-watered greenhouses.

A second production system is the greenhouse float system, which utilizes Styrofoam trays or "floats" that are filled with soilless media and floated in shallow, water-filled bays. Floats may hold 200 to 392 plants, producing 884 to 1744 plants per square meter, respectively. Fertilizer is dissolved in the water and thus constantly available to the tobacco seedlings. Growth is regulated primarily through clipping of the seedlings with a rotary mower that is hung from a rail that passes over the plants. Clipping is necessary to increase transplant uniformity in direct-seeded float or overhead-water greenhouses. Although float greenhouses are direct-seeded, small-scale float systems may be used for hand transfer of purchased miniplugs (commercially grown seedlings) or small seedlings that growers may start themselves. Float beds used for miniplugs or seedling transfer are generally very small, producing limited acres of transplants, but do not require the heating systems necessary for germination of direct-seeded floats. The disadvantage of transfer beds is the labor required for hand transfer of the young seedlings. Direct-seeded greenhouses may be used to produce as much as 150 to 200 acres of transplants.

Proper management is very important for successful transplant production in either a greenhouse or outdoor float bed. Sanitation is essential to prevent pest problems, and contamination with field soil must be avoided to prevent the introduction of soil-borne pathogens in the greenhouse. Trays used for seedling growth and all equipment that may come in contact with plants should be kept clean and sanitized to prevent the introduction and spread of pathogens. Proper greenhouse ventilation and air movement are necessary to prevent high temperatures that may injure or kill young seedlings. The typical greenhouse used for tobacco transplant production has side curtains that are raised and lowered to allow for proper ventilation. Air movement in the greenhouse may be further enhanced with the use of "horizontal airflow" fans that are suspended from the top of the greenhouse to provide a circular pattern of air movement throughout the greenhouse. Unlike outdoor plant beds, water quality is an important consideration of greenhouse transplant production. Water analysis can be used to determine the most appropriate fertilizer and whether water treatment is necessary.

B. Leaf Production

1. Fundamental Soil Considerations

Soils best suited for tobacco production tend to have a well-drained, open-textured topsoil with good water-holding capacity over a heavier-textured, more clayey subsoil. Tobacco producers can maintain and improve soil tilth and quality by rotating tobacco with other crops, by appropriate tillage, and by using recommended practices to minimize soil pests. Tobacco is a heavy user of soil nutrients and thus commercial production requires the addition of relatively high levels of fertilizer. The practice of regular soil sampling and analysis is important to determine the most appropriate and economical fertilization program, and whether the addition of lime is necessary. Soils used for flue-cured tobacco are generally infertile and the grower relies on proper fertilizer selection and precise application to provide sufficient amounts of necessary nutrients in the most appropriate forms. Other tobacco types may be grown on more fertile soils, although the addition of fertilizer is necessary to provide sufficient nutrient levels at the appropriate time for crop development. [*See* FERTILIZER MANAGEMENT AND TECHNOLOGY.]

2. Fertilization

Nitrogen is the most important nutrient in tobacco production. How well the crop matures and ripens depends on the amount and availability of nitrogen. Nitrogen rates vary from 56 to 112 kg/ha for flue-cured tobacco to 140 to 280 kg/ha for burley and dark tobaccos (see Table I). Although green manures may be used with most tobaccos, their use must be avoided with flue-cured tobacco as nitrogen availability is critical for proper maturation and ripening. Tobacco is also a heavy user of potassium or potash (K_2O) with normal use rates of 112 to 168 kg/ha. Soils commonly used for tobacco are inherently low in phosphorus. However, years of tobacco production and the use of high-phosphorus fertilizers have resulted in a buildup of soil phosphorus levels in most fields used for tobacco. The phosphorus recommendation for most tobacco soils is 45 to 90 kg/ha.

A typical fertilization program includes two applications of fertilizer. Usually a complete fertilizer, containing nitrogen, phosphorus, and potassium, is applied either before, at the time of, or shortly after tobacco is transplanted in the field. Depending on phosphorus soil test levels, the analysis ratio (N : P : K) of the complete fertilizer will be 1 : 1 : 3, 1 : 2 : 3, or 1 : 3 : 3. A second application of nitrogen or nitrogen and potassium (depending on soil analysis) is made during an early cultivation of the crop. The sidedress fertilizer analysis ratio will depend on potassium soil test levels and may be either 1 : 0 : 0, 1 : 0 : 1, or 1 : 0 : 3. Care must be taken during fertilizer applications that too much fertilizer is not applied at one time or placed too closely to the roots of young plants. Otherwise, root injury and stand losses may occur due to high fertilizer salts levels.

A typical tobacco crop may remove approximately 62 and 25 kg/ha of calcium and magnesium, respectively. Fertilization specifically for these two essential nutrients is generally not necessary as both are supplied in complete analysis fertilizers used for tobacco, and from lime applied to maintain proper soil pH. The pH of tobacco soils should be maintained between 5.6 and 6.2 to ensure proper micronutrient availability and to remain compatible with other crops grown in tobacco rotations. Although a number of micronutrient deficiencies have been observed in tobacco, their occurrence is not common; therefore, specific micronutrient fertilization is not generally required.

3. Land Preparation and Cultivation

Fields in which tobacco is to be grown are prepared by plowing with a moldboard or chisel plow and disked to prepare 25 cm of loose soil and good tilth within the top 12 cm. The soil should be free of clods and fine enough to allow firming of the soil around the transplant. Tobacco is generally planted into raised beds or ridges to provide better drainage and aeration of the soil around the plant. However, not all tobacco is planted into beds owing to the time and expense of the bedding operation and the potential for beds to dry excessively. [*See* TILLAGE SYSTEMS.]

Tobacco is usually cultivated two to four times to control weeds, to prevent soil crusting (thus increasing water penetration and improving soil aeration) and to place soil around the base of the plant. Each cultivation is directed to successively build up a row ridge to improve surface drainage and reduce the chance of plants drowning in waterlogged soils. The last cultivation occurs near the point when the plants become too tall to pass under the equipment used for cultivation and is called the "layby" cultivation. Application of certain herbicides and fungicides to the soil may occur with the layby cultivation.

No-till or reduced tillage has been researched and evaluated for several years as a way of reducing potential soil loss in tobacco production. The yield and quality of such tobacco are usually slightly lower than with conventionally grown tobacco. However, the development of better broadleaf herbicides for tobacco promises to alleviate some of the limitations of reduced tillage production.

4. Topping and Sucker Control

The production of tobacco with acceptable quality and high yields requires the topping and control of sucker growth. Topping is the removal of the apical bud at the time of inflorescence bud emergence and development. Allowing the flower to fully develop diverts resources from leaf production, thus reducing the yield and quality of the cured tobacco. The height or number of leaves per plant will vary according to tobacco type (see Table I). To produce maximum yield, plants should be topped as soon as they reach the desired stage.

Topping is generally done by hand, although some flue-cured tobacco growers have adopted mechanical topping machines to reduce hand labor requirements. Removal of the "top" or inflorescence breaks apical dominance within the plant and allows axillary buds or "suckers" present in each leaf axial to develop and grow. Allowing suckers to grow will reduce yield and is detrimental to the quality of the cured tobacco. In early tobacco culture, suckers were regularly removed by hand in a procedure called "suckering." Chemical growth regulators are now used to minimize the growth of suckers and greatly reduce the hand labor required. The use of these materials was first developed in the 1940s. Today, chemical sucker control usually involves the sequential application of one or more materials. Contact chemicals (fatty alcohols) act upon young, actively growing suckers through desiccation. Systemic chemicals act by preventing cell division either locally (flumetralin) or throughout the entire plant (maleic hydrazide).

5. Pest Control

Diseases, insects, nematodes, and weeds can severely damage tobacco crops. Although diseases and nematodes are often considered bigger problems for tobacco than insects and weeds, virtually all tobacco producers must include insects and weed control practices in their tobacco production plans.

Table II lists many of the most important tobacco diseases. Many of these syndromes (e.g., black shank) kill plants by destroying plant roots. Plant-parasitic nematodes are microscopic roundworms that live in soil and feed on roots, particularly of flue-cured tobacco. Root-knot nematodes are the most important nematode pests of tobacco. Because leaves are the part of the tobacco plant that is harvested and sold, foliar diseases can severely reduce tobacco yield and quality. Fungi and bacteria cause a number of leaf spot diseases that are important tobacco problems, especially blue mold. A number of viruses can also stunt tobacco plants and severely distort tobacco leaves. Various fungi cause molds or rots that damage cured tobacco leaves in storage. Parasitic plants can also infect tobacco plants: broomrape (species of *Orobranche*), witchweed (*Striga gesneroides*), and dodder (*Cuscuta campestris*) can infect the stems or roots of tobacco plants and remove nutrients that would otherwise be used to increase tobacco yield and quality.

Crop rotation, early destruction of tobacco debris after harvest, and resistant varieties are the foundation of tobacco disease control. Growers are highly encouraged to use all of these practices together, rather than relying on only one method to control a disease problem. However, pesticides are frequently needed to control diseases and nematodes in tobacco fields either because pathogen populations are so large that

TABLE II
Important Diseases of Tobacco

Root and stem diseases		Foliar diseases	
Common name(s)	Causal agent(s)	Common name(s)	Causal agent(s)
Fungi			
Black root rot	*Thielaviopsis basicola* (Berk. & Br.) Ferr.	Anthracnose	*Colletotrichum gloeosporoides* (Penz.) Penz. & Sacc.
Black shank	*Phytophthora parasitica* Dast. var. *nicotianae* (B. de Haan) Tucker	Blue mold	*Peronospora tabacina* Adam
Charcoal rot	*Macrophomina phaseolina* (Tassi) Goidanich	Brown spot	*Alternaria alternata* (Fr. ex Fr.) Kiessel.
Collar rot	*Sclerotinia sclerotiorum* (Lib.) de Bary	Frogeye	*Cercospora nicotianae* (Ellis & Everh.)
Damping-off	*Pythium* spp. *Rhizoctonia solani* Kühn	Gray mold or dead blossom leaf spot	*Botrytis cinerea* Pers.:Fr.
Fusarium wilt	*Fusarium oxysporum* ex Fr. f. sp. *nicotianae* (J. Johnson) W.C. Snyder & H. N. Hans.	Ragged leaf spot	*Ascochyta nicotianae* Pass.
Sore shin	*Rhizoctonia solani* Kühn		
Southern stem rot or blight	*Sclerotium rolfsii* Sacc.		
Tobacco stunt	*Glomus macrocarpus* (Tul. & Tul.) and *Glomus microcarpus* (Tul. & Tul.) Gerd. & Trappe.		
Verticillium wilt	*Verticillium dahliae* Kleb.		
Bacteria			
Granville or bacterial wilt	*Pseudomonas solanacearum* (Smith) Smith	Angular leaf spot and and wildfire	*Pseudomonas syringae* pv. *tabaci* (Wolf & Foster) Stevens
Hollow stalk and black leg	*Erwinia carotovora* subsp. *carotovora* (Jones) Bergey *et al.*		
Nematodes		**Viruses**	
Brown root rot or lesion	*Pratylenchus* spp.	Alfalfa mosaic virus beet curley top virus cucumber mosaic virus	
Root-knot	*Meloidogyne incognita* (Kofoid & White) Chitwood, *M. arenaria* (Neal) Chitwood, *M. javanica* (Treub) Chitwood, *M. hapla* Chitwood	peanut stunt virus potato virus Y tobacco etch virus tobacco leaf curl virus tobacco mosaic virus tobacco necrosis virus tobacco rattle virus tobacco ringspot virus tobacco streak virus tobacco stunt virus tobacco vein mottle virus tomato spotted wilt virus	
Stem break	*Ditylenchus dipsaci* (Kuhn) Filipjev		
Tobacco cyst	*Globodera tabacum* subsp. *solanacearum* (Miller & Gary) Behrens, *G.t. tabacum* (Lownsbery & Lownsbery) Behrens, or *G.t. virginiae* (Miller & Gray) Behrens		

they overwhelm the effects of these cultural practices or because some other factor prevents effective use of one or more of these cultural control methods. Although fungicides are commonly applied to tobacco plant beds, most tobacco disease control chemicals are applied to fields just before transplanting. Pesticides for control of diseases or nematodes are rarely applied directly to tobacco leaves in the field. [*See* NEMATICIDES; PEST MANAGEMENT: CULTURAL CONTROL.]

Although a principal constituent of tobacco leaves (nicotine) is used to control insects on other crops, insect pests remain an important problem in tobacco production. Some insects that damage tobacco avoid nicotine by feeding on plant tissues with minimal levels of nicotine, whereas others have developed metabolic pathways to excrete or detoxify nicotine before the chemical can exert negative effects upon them. Most of the important insect pests of tobacco are listed in Table III.

Early destruction of tobacco roots and stalks after harvest and early topping and effective sucker control practices are encouraged to reduce overwintering populations of insect pests. Early topping and improved sucker control practices are also promoted to improve control of aphids and hornworms. Transplanting earlier and avoiding excessive use of fertilizers are also recommended to improve control of tobacco insects. However, insect control in tobacco remains even more dependent on pesticide use than control of diseases and nematodes. No insect-resistant varieties are available, and cultural methods to reduce pest incidence are usually insufficient to provide acceptable control by themselves. Insecticides are usually applied to tobacco fields just before transplanting to control soil insects. Some soil insecticides also control some foliar insect pests, but insecticides are commonly sprayed on tobacco fields during the growing season on an as-needed basis. Many tobacco growers in the United States now use biocontrol (in the form of a *Bacillus thuringiensis* bait) to control budworms.

TABLE III
Important Insect Pests of Tobacco

Common name(s)	Scientific name
Insects that damage roots and stems	
Cutworms	*Agrotis, Feltia, Peridroma,* and *Spodoptera* spp.
Flea beetles	*Epitrix hirtipennis* (Melsheimer)
Mole crickets	*Scapteriscus* spp.
White fringe beetles	*Graphognathus* spp.
Wireworms	*Conderus vespirtinus* and *C. falli*
Insects that damage leaves in the field	
Aphids	*Myzus nicotianae* Blackman
Budworms	*Heliothis virescens* (Fabricius)
Cabbage loopers	*Trichoplusia ni* (Hübner)
Flea beetles	*Epitrix hirtipennis* (Melsheimer)
Grasshoppers	*Melanoplus* spp.
Hornworms	*Manduca* spp.
Japanese beetles	*Popillia japonica* (Newman)
Potato tuberworms	*Phthorimaea operculella* (Zeller)
Stink bugs	*Acrosternum, nezara,* and *Euschistus* spp.
Thrips	*Thrips tabaci* and *Frankliniella* spp.
Whiteflies	*Bemisia tabaci* (Gennadius)
Insects that damage stored tobacco leaves	
Cigarette beetles	*Lasioderma serricorne* (Fabricius)
Tobacco moths	*Ephestia elutella* (Hübner)

Weed control is an important part of producing a quality tobacco crop because weeds compete with tobacco for fertilizer, sunlight, and water. Weeds also increase trash in harvested tobacco and provide alternate hosts for tobacco pests and diseases. Crop rotation and properly timed and executed tillage and cultivation practices often provide significant weed control for tobacco. Hand-hoeing of tobacco plant beds and fields remains an important part of tobacco weed control, especially for small farmers. However, herbicides are commonly used where persistent weed problems exist and where labor costs for hand-hoeing are prohibitive, particularly for flue-cured tobacco in the United States. Most tobacco weed control programs focus on minimizing weed populations in plant beds and fields until the crop is large enough to shade out weed seedlings. Although most grasses can usually be controlled in tobacco fields, broadleaf weeds can sometimes choke whole tobacco fields, even when all available weed control methods have been used. All currently available tobacco herbicides act by inhibiting the germination of weed seed. Consequently, tobacco plant beds are fumigated with methyl bromide before seeding and tobacco fields are treated with herbicides just before transplanting. Herbicides are also sometimes applied to tobacco fields just after the final cultivation to provide full-season weed control. Minimal weed growth during the harvest season is particularly important when mechanical harvesters are used. [*See* WEED SCIENCE.]

6. Tobacco Harvesting Systems

The timing of tobacco harvest is a critical factor in tobacco production. Growers try to harvest only "ripe" tobacco; "mature" tobacco leaves have reached their full size and operate at maximum effectiveness. Ripe tobacco leaves are mature, but are no longer operating at peak efficiency. Farmers detect the onset of this senescence by a chlorosis or yellowing of tobacco leaves that results from the breakdown of chlorophyll. The intensity of these changes varies for each tobacco type and may also be influenced by environmental conditions. This yellowing indicates that carbohydrate and nitrogenous compounds within the leaves are being converted into more soluble, mobile forms. Tobacco ripeness is a physiological state occurring after this conversion has begun but before the process has advanced to the point that these compounds have actually left the leaves.

Flue-cured, cigar-wrapper, and oriental tobaccos are sequentially harvested or "primed" because they need to have a relatively high sugar content. Sequential harvesting of individual leaves allows these tobacco types to continue conversion of carbohydrates to reducing sugars for a longer period of time. Delayed harvesting also generally results in lower levels of nitrogenous compounds such as nicotine. Leaves toward the bottom of the stalk usually ripen before those toward the top of the plant. Several (three to five) flue-cured tobacco leaves are primed at each harvest. Priming aids or "taxi-type" harvesters were introduced in the 1950s that transported harvest labor through flue-cured tobacco fields. Mechanical leaf-tying machines were developed in Canada and spread throughout the United States. A machine for harvesting flue-cured tobacco was introduced in 1971. Mechanical harvesting of flue-cured tobacco is becoming more common as labor costs continue to rise. Other tobacco types, such as air-cured tobaccos and burley, are harvested by cutting stalks just above the soil. Harvested plants are left in the field until their leaves begin to wilt. After wilting, plants are placed in curing barns, where leaves are cured while remaining attached to plant stalks.

7. Curing Tobacco

Curing tobacco involves the use of ventilation and temperature to reduce the water content of harvested leaves in order to manage the continued conversion of carbohydrates within tobacco leaves to simple sugars such as glucose, fructose, and sucrose. The length of time that tobacco is cured directly influences the sugar content of the final product. Farmers learned to smoke tobacco in the curing process to minimize rots and to prepare the leaf for storage and transport to market. Early in the nineteenth century, planters in North Carolina and Virginia began to use heat in the curing process to cure leaves to an even lighter color, a golden yellow. The use of flues to supply fireboxes from fuel outside of the barn was patented by Dr. David G. Tuck of Halifax, Virginia, in 1830. However, flue-curing did not become widespread until after the Civil War. Flue-curing of primed leaves was not completely adopted in the United States until almost 1920. Flues were gradually replaced by thermostatically controlled burners that used oil or gas. "Bulk-curing" was first used on a farm in Robeson County, North Carolina, in 1960. This new curing method reduced harvesting labor by 50% compared to use of conventional barns that contained leaf tied onto wooden sticks. Almost all flue-cured tobacco grown in the United States is now bulk-cured.

Flue-cured tobacco is cured for only 3–6 days, resulting in relatively high levels of reducing sugars. Wet and dry bulb thermometer readings are used to manage airflow, relative humidity, and temperature within curing barns. R. L. Ragland of Virginia proposed the curing regime for flue-cured tobacco that is still being used today. His process included four distinct stages: (1) yellowing of the leaf, (2) fixing the color of the leaf, (3) drying the leaf, and (4) drying the leaf stems. In the "yellowing stage," fans recirculate air through the harvested leaves to minimize molds and rots while air temperatures within the curing barns are raised very gradually. Almost all the starch in the leaves is converted to sugars during this stage. The degree of carbohydrate-to-sugar conversion is judged based on the intensity of the change in leaf color from green to yellow. Once the yellowing phase has been completed, chemical changes within the leaves (indicated by leaf color) are "fixed" by increasing temperatures and the proportion of ambient to recirculated air to dry the leaf lamina. The final "killing-out" stage of curing flue-cured tobacco involves increasing air temperatures further to remove remaining moisture from within leaf stems to prevent seepage of water back into leaf lamina and to minimize problems with storage rots and molds.

Sun-cured tobaccos are cured for 2–4 weeks, without any precise controls. Some air-cured types, such as oriental, are not cured within a structure but dry out on racks in shady areas with minimal protection from the weather. Most air-cured types, however, are cured within barns for 3–6 weeks. This slow and gradual process minimizes the sugar content of these types of tobacco. The amount of environmental control used during curing varies, but the walls and roofs of curing barns usually allow growers to adjust airflow through the barns to some degree. Artificial heat or fans are used only in rare cases of excessively moist conditions.

Fully cured tobacco leaves are dry and too brittle to be handled easily. This condition limits storage problems, but must be corrected to market the product. Therefore, one of the first stages of market preparation is often to "condition" or bring the tobacco "in order". Under humid conditions, cured leaves can absorb enough atmospheric moisture to become soft and malleable. However, in some tobacco production areas, and in some years, cured leaves must be steamed or misted prior to being sold.

8. Marketing Tobacco

Cured leaf was originally packed into hogsheads and shipped overseas. Later, tobacco was sold through inspection warehouses, followed by sales "at the barn door" to domestic dealers and manufacturers. Loose leaf sales of flue-cured tobacco were first recorded at Neel's Warehouse in Danville, Virginia, in 1858, where tobacco was sold in stacks of hand-tied bundles, called "hands." Flue-cured tobacco was sold in piles of untied tobacco beginning in the 1970s. Burley marketing switched to bales of untied leaves in the late 1970s and early 1980s. Inspection and use of standardized federal grades of U.S. tobacco on warehouse floors was initiated in 1929. Growers were required to predesignate warehouses for marketing their crop beginning in 1974.

Cured tobacco leaf is generally sold at auction. Flue-cured tobacco producers in the United States bundle loose leaf in large burlap sheets. These bundles are lined up on the floor of an independently owned warehouse. Sheets are untied to allow government graders to classify the tobacco according to a system that attempts to describe leaf size, color, and physical condition. Tobacco is sold as auctioneers and buyers move along the rows of sheets taking bids on each pile of tobacco. Burley tobacco is sold similarly, with the exception that farmers sort burley tobacco leaves as they strip them from plant stalks, and then press the cured leaves into bales. Other tobacco types are still prepared for market by tying into "hands" composed of several leaves that are twisted or tied together. These hands are placed in neat piles for presentation at the warehouse or sales area. Dark air-cured tobacco in Kentucky is purchased while still in the curing barn. In Brazil, individual tobacco farmers contract with a buyer before planting. In some African countries, producer cooperatives process the tobacco and market the crop by auction or private contract.

Tobacco producers are not directly identified in auction systems for marketing tobacco as codes are used to keep track of a producer's crop. This pseudoanonymity helps preserve the rights of both buyers and sellers to nullify a sale for appropriate reasons. In the United States, tobacco producers who do not receive an auction price equal to or higher than a "support price" can place their tobacco under loan to a government-administered, producer-owned cooperative for a designated "support price." The cooperative processes and stores the leaf and attempts to sell it via a bidding system. This system was instituted to stabilize supply and demand for tobacco. The system also guarantees a minimum price for U.S. producers.

III. Tobacco Propagation for Research

All *Nicotiana* species produce very small seeds (10,500/g for *N. tabacum*) and delicate seedlings. Seed should be sown in a sterile medium such as vermiculite, a sterilized sand : loamy soil : peat moss mixture, or fumigated soil. A 10-cm pot should be sown with 40–50 seed. Seed should be covered with a fine layer of medium after sowing, which needs to remain moist until emergence, but should not be watered from above. Seedlings should emerge within 5–7 days at ambient air temperatures between 21 and 27°C. Species other than *N. tabacum* may take as long as 30 days to germinate. Seedlings in vermiculite should be fed with 150 ml of Hoagland's solution 1 and 2 weeks after germination. Freshly harvested seed may be dormant, which can usually be overcome by placing seed in a 2% sodium hypochlorite solution (2:3 solution of bleach and water) for 15–30 min. Treated seed should be rinsed with water and placed briefly in acetone. Seedlings should be transplanted into 5-cm-diameter containers when they are about 4 cm tall. Plants should be fed weekly with Hoagland's solution, but care should be exercised to avoid overwatering. *Nicotiana* species that produce large mature plants should be transplanted a second time about 3–5 weeks after the first transplanting.

Most *Nicotiana* species can be asexually propagated, although with varying difficulty, using stem cuttings, axillary shoots (suckers), or leaves. *Nicotiana* species can also be grafted. Haploid plants are very useful for research because they can be cultured in large numbers, screened for any number of inherited traits, and then transformed back into a diploid state. Viable plants of *Nicotiana* species can be obtained by culturing either anthers or pollen. The ploidy status of haploid plants is usually confirmed (often by root tip cytology) before treatment to convert them back to a diploid state. Diploid plants may be obtained by culturing midvein sections from mature leaves of diploid plants or by culturing plants from axillary buds treated with colchicine. Vegetative organs of *Nicotiana* species may also be cultured separately. Root cultures are initiated by germinating disinfected seed and then incubating the seed on a sterile rooting medium. Shoot tip culture involves removing and surface sterilizing the apical 1 cm of a plant stem, cutting the meristematic tissue from the bud, and transferring the tissue to a sterile rooting medium. Leaves can be cultured by transferring meristematic tissue onto a suitable nutrient medium that does not stimulate root formation. Plant reproductive organs can also be cultured for research purposes.

Nicotiana species were among the first used in developing plant tissue culture methods and are a commonly used model system in basic plant research. Cells are usually obtained by aseptically transferring pith tissue from within plant stems onto a solid agar or liquid growth medium. Cultures are incubated in the dark under moist conditions for 3–5 weeks. Once established, callus tissues need to be transferred frequently to maintain an uninterrupted supply of healthy, continuously growing plant cells. However, these techniques also have a number of limitations. Wherever possible, therefore, tissue cultures need to be compared with intact plants. Cultures need to be checked periodically against the specific plant from which the original culture was taken to verify that the culture retains sufficient resemblance to the original explant.

IV. Tobacco Products

Tobacco is currently produced by farmers for the commercial manufacture of products that are smoked (cigars, cigarettes, and pipe tobacco) or chewed (chewing tobacco, snuff). Once sold, tobacco is grouped by purchasers into homogeneous mixtures of leaves with a similar "style." These mixtures possess a specific set of desired characteristics that is described by a classification system that may be unique to each manufacturer. The midribs of leaves are then separated from leaf lamina in a process called "stemming." Lamina and stems are then "redried" separately and packed for storage. Cured leaf is stored under conditions to minimize insect damage, molds, or loss of color. Leaf is often stored for up to 18 months before use.

The most commonly used type of cigarette is known as the "American blended" cigarette. It is so known because of the extreme degree to which burley, flue-cured, Maryland, oriental, and reconstituted tobaccos are mixed or blended with various additives to result in a given taste and aroma. Blended cigarettes, versus those made from a single or limited number of tobacco types, originated in the United States. This style of cigarette is increasingly replacing other types because blended cigarettes are characteristically milder.

Cigarette manufacture initially involves processing leaf to obtain a thorough mixture of tobacco cut into small pieces, followed by inserting this mixture into a paper tube to form a cigarette. The manufacturing process requires precise control of the moisture content of the tobacco. For this and a number of other reasons, each of the different tobacco types used in blended cigarettes is initially processed separately.

When tobacco is removed from storage for cigarette manufacture, it is first "conditioned," "ordered," or "brought into case" by adding moisture. Flavorings and other additives are also often added to leaf lamina of burley tobacco at this stage of processing. "Casing" is the process of adding flavorings and modifiers to tobacco by soaking, spraying, or dipping leaf lamina before it is cut into narrow strips called "rag." Cased tobacco is "toasted" at high temperatures to reduce harshness, and then reordered. Sugars, herbs, botanical oils, resins, and gums are added to tobacco to improve taste and aroma and to improve the moisture-holding capacity of the tobacco. These additives may be applied before (casing) or after cutting. Additives are also sometimes applied to cigarette packaging.

Leaf stems are preconditioned with water and then crushed. In many countries, crushed stems are cut, dried, and cooled before use or storage. In the United States, water-soluble materials are removed from crushed stems, mixed with additives, and then added back to a fibrous matrix to form "reconstituted sheet."

The processing lines for each type of tobacco merge just before the tobacco is cut into rag. This cutting operation cuts the tobacco into narrow strips, the width of which influences smoking characteristics, as well as the firmness of the cigarette. The cut rag is then deposited onto paper fed from large bobbins. Most cigarette paper is made from flax and must possess a uniform and precise permeability to allow cigarettes to burn properly. Cigarette paper also tends to hold cigarette ash together to minimize flaking of hot ash outward during smoking. The paper is rolled and gummed around cut tobacco rag to form a long cylinder that is cut into appropriate lengths. Filters, if desired, are placed on the cut cigarettes by a separate machine that is integrated with the cigarette maker. Paper or cellulose acetate fibers (called "tow") within cigarette filters remove particulate matter from tobacco smoke. Carbon is also sometimes used in cigarette filters to remove certain gases from inhaled tobacco smoke.

Cigars may be hand-rolled or manufactured by machine. They are composed of 85% "filler," 10% "binder," and 5% "wrapper" type tobaccos. Binder and wrapper tobacco are often made from reconstituted tobacco sheet. Filler tobacco is rolled into a cigar shape and wrapped in binder tobacco to produce a "bunch." A wrapper leaf is spiraled around the outside of each bunch, from the fire to the head end, to prevent the cigar from unwrapping as it is being smoked.

Pipe tobaccos are blended and conditioned similarly to cigarette manufacture, though the tobacco is maintained at a higher moisture content. Heavier styles of burley and flue-cured tobacco may be blended with heavy sun-cured, air-cured, or fire-cured leaf. Pipe tobacco is sometimes heavily cased. Small quantities of Perique or Latakia tobacco may also be included in blends of pipe tobacco. Tobacco rag may be cut in varying widths for pipe tobacco and may be baked or pressed.

There are four types of chewing tobacco: loose or scrap leaf, plug, fine-cut, and twist. Most chewing tobacco today is loose leaf, which is mostly dark air-cured tobacco from Pennsylvania and Wisconsin. Leaves are stemmed and cut and may or may not be heavily cased with sweeteners. Plug chewing tobacco is the original type of chewing tobacco. Leaves were soaked in honey and "plugged" into green hickory or maple logs in Kentucky and Missouri, and rum and licorice were frequently added as well. Plugs are now manufactured by pressing leaves in a mold and wrapping the plug with fine-textured, elastic leaves, usually flue-cured tobacco. Fine-cut chewing tobacco is manufactured from air-cured and fire-cured tobacco produced in Kentucky, Tennessee, and Virginia. It is held between the cheek and gum, rather than being chewed. Twist-type chewing tobacco is composed of burley, air-cured, and flue-cured tobacco leaves that are twisted together.

Snuff is manufactured from fire-cured and dark air-cured tobacco. Leaves are packed and aged as for other uses, but are heavily reconditioned and repacked to ferment for about 2 months. Fermented tobacco is dried and ground into a fine powder that may be blended with flavorings or scents or left plain. Dry snuff is held between the lower lip and the gum of the user. Wet snuff, like fine-cut chewing tobacco, is held between the cheek and gum. Europeans, however, inhale snuff through each nostril. Some North Africans consume a wet snuff made from leaves of *N. rustica*.

V. Future Uses of Tobacco

Tobacco is one of the plant species most widely used in basic agricultural and botanical research. Many call it the "white mouse" or the "*Escherichia coli*" of the plant kingdom. Much research has also been conducted to identify uses for tobacco other than for human consumption. Some of these uses have existed for many, many years, and others involve technological innovations on the forefront of science. Most alternative uses involve using various parts of the tobacco plant or require extraction of certain specific components from tobacco leaves. Nicotine has been used for centuries as a natural insecticide, and tobacco can also be used as a fiber source to produce paper. Research has also evaluated tobacco for use as poultry feed, animal bedding, and as a fertilizer and soil conditioner. The use of tobacco stems and stalks to retain ammonia gas in poultry manure has also been investigated.

Most of the exciting new uses for tobacco involve manipulation of tobacco physiology to obtain products other than nicotine. Tobacco leaves are a chemical factory that could be manipulated to produce industrial chemicals and food supplements. Half of the soluble protein in tobacco is a type of protein referred to as Fraction I protein, which is a tasteless, odorless substance that can be extracted from tobacco in an extremely pure form. It also has an amino acid composition very similar to that of milk, giving it a specific nutritive value for humans that is much higher than that from soybeans, and even comparable to that of human milk. Tobacco also produces relatively large quantities of Fraction II protein, which has a specific nutritive value only slightly lower than that of Fraction I types. In addition, tobacco plants have already been developed, through the use of biotechnology, that produce valuable antibiotics and enzymes. Research is continuing to develop practical and commercially viable tobacco production systems focused on industrial proteins and enzymes, pharmaceuticals, and antibiotics.

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Tomato Production in Protected Cultivation

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Glossary

Photomorphogenesis Influence of light on the development and organizational structure of a plant

Plant factory Ultimate in controlled environment agriculture where all aspects of the production cycle are under the control of the grower; this system is based on the belief that we know exactly what the plant needs and when it needs it; the development of such a system would allow a grower to control and predict production much like in a factory, where the system can be made as efficient as possible

Plant growth model Blueprint from which a grower can work; such a model is based on a basic understanding of the crop and how it will respond to environmental changes at any time during its developmental cycle

Soilless culture Production of plants in a medium other than natural soil; this includes the use of a totally liquid growing medium (hydroponics) or the use of an aggregate such as peat, vermiculite, perlite, gravel, or sand either alone or in combination; the medium must be sterile and be able to provide the plant with nutrients and air without releasing any toxic material into the nutrient solution

Tomatoes are consumed worldwide. They are produced primarily in the field and can be shipped to areas where environmental conditions prevent field production in all or part of the year. Generally, the production of tomatoes miles and/or days from the point and/or time of sale will result in a product with reduced quality. It is possible to grow tomatoes year round at a point close to consumption on a commercial basis under controlled environmental conditions (i.e., greenhouses). Through a description of the methodologies used to grow greenhouse tomatoes, we will explore the production of a quality product by accurate environmental control and manipulation. Remember there can be two ways in which yield and quality can be enhanced. One is by breeding a new cultivar with certain desirable characteristics. The second, and the one explored here, is through an understanding of how temperature, light, humidity, CO_2 and nutrition interact to effect the plant during different stages of development.

I. Introduction

Tomato fruit are produced and consumed worldwide (over 135,000,000 tons/year). They can provide between 20 and 40% of an adult's requirement for vitamins A and C based on an average of 100–125 g of tomato consumed per average salad. Table I lists the nutritional content of a 100-g tomato. The popularity of the tomato rests not only on its wide production range but also on its unique flavor. The perception of flavor is influenced by many chemical constituents. Primary among these are sugars and acids that interact to provide sweetness, sourness, and flavor intensity. Usually high sugars and high acids are needed for the best flavor. In tomato, fructose and citric acid are of primary importance in flavor development. The fleshy part of the fruit contains sugar but not much acid, whereas the gel contains high acid. Usually fruit with high gel content and both high sugar and acids are perceived to have better flavor. Table II lists some of the main chemical constituents in a ripe tomato fruit.

The quality of the fruit relies not just on the flavor but also on the firmness, shelf life, and appearance of

TABLE I

Nutritional Information for a 100-g Tomato

Calories	23
Water	94%
Protein	0.8 g
Carbohydrates	4 g
Fat	0.6 g
Cholesterol	0
Crude fiber	0.6 g
Minerals and vitamins	
Sodium	8 mg
Potassium	21 mg
Vitamin A	1100 IU (22% RDA)
Vitamin C	18 mg (30% RDA)
Thiamin	0.05 mg (3% RDA)
Riboflavin	0.05 mg (3% RDA)
Niacin	0.6 mg (3% RDA)
Iron	0.5 mg (3% RDA)
Folic acid	0.01 mg (2.5% RDA)

Source: Nutritive value of foods. *Home and Garden Bull.* **72,** 56–61. Human Nutrition Information Service, U.S. Department of Agriculture.

the fruit. Generally speaking these latter features are more important than flavor to marketers and distributors. Appearance refers to size, shape, color, and defects. Tomatoes are often picked at a "green" stage (see Table III for ripeness classification) and shipped great distances to market. These fruit ripen in transit and can be treated with ethylene gas to promote ripening. With this procedure, tomatoes with good appearance can be marketed many miles and several days from the field. However, the flavor may suffer when fruit are harvested prior to the "breaker" stage with the development of off-flavors or lack of flavor. Fruit harvested at the "breaker" stage and held at 20°C will develop the best overall flavor and appearance. "Mature green" fruit can be stored for up to 7 weeks at 4% O_2, 2% CO_2, and 5% CO. These fruit can still attain a marketable quality for an additional 1–2 weeks at 20°C, however, flavor will suffer.

TABLE II

Organic Chemical Content of Tomato Fruit as Percentage of Dry Weight

Protein	8
Glucose	22
Fructose	25
Sucrose	1
Citric acid	9
Malic acid	4
Minerals	8
Cellulose	6
Pectin	7

Source: J. G. Atherton and J. Rudich (eds.). (1986). "The Tomato Crop." Chapman & Hall, New York.

TABLE III

Ripening Stages

Stage	Description
Green	Mature size, entirely light to dark green
Breaker	First appearance of pink, no more than 10% of surface
Turning	More than 10% but less than 30% of the surface is pink
Pink	More than 30% but less than 60% of surface is pink
Light-red	More than 60% but less than 90% of the surface is red
Red	Over 90% of the surface is red, ripe

Source: Retail Guide, (1994) California Tomato Board, Fresno, CA.

Tomato quality depends on developing the proper appearance and flavor during both the preharvest growing period and the postharvest handling period. The focus of this section will be the preharvest "growing" conditions. In an even more narrow sense we will concentrate on the environmental conditions necessary to produce quality fruit. This will be done within the framework of the production of tomatoes in protected cultivation.

In places where the natural environmental conditions prevent the production of tomatoes in the field, fruit can be produced in controlled environmental facilities, usually greenhouses. These facilities are used to produce high-quality fruit at an increased cost to the consumer. The increased retail price is paid because of the availability of quality product when normally only poorer-quality fruit transported great distances are available. The ability of the greenhouse grower to manipulate the environment has led to research elucidating climatic influences on tomato growth and development. In addition, unique production systems have been developed that incorporate this knowledge in a cost-conscious manner. Indeed, the modern commercial greenhouse operation is making a slow but steady transition from a general farming operation to a highly sophisticated plant factory, a place where a computer is a valuable tool in day-to-day operations as well as in long-term decision making. The ability to control the growing environment, coupled with a more thorough understanding of tomato growth, has provided the impetus for this transition. [*See* HORTICULTURAL GREENHOUSE ENGINEERING.]

This article will describe what can be done environmentally in the greenhouse and give some examples of plant responses to these manipulations. Given that one goal of the commercial grower is to minimize operational costs by reducing energy inputs while optimizing profits from the best possible plant growth, an understanding of plant–environment interactions that lead to the development of plant growth models is necessary to accomplish this goal.

The concept of growing quality crops on a predictable and controllable basis, that is, in a plant factory, is becoming a reality. However, much work needs to be done, particularly in the area of plant response to various temperature, light, CO_2, humidity, and nutrient levels at different stages of plant development. Additionally, we will address some of the economic considerations necessary to a viable business, as well as some of the various production methods in use today and some possibilities for tomorrow.

II. Environmental Control of Tomato Growth

A. Temperature

A greenhouse is totally dependent on its heating and cooling systems. Energy is used to operate vents, fans, boilers, and pumps in an attempt to maintain temperatures acceptable for plant growth. Greenhouses are intensive consumers of energy and energy costs are a significant part of the operational expenses. On the other hand, productivity in greenhouses can be over four times greater than that in the same area of field. Therefore, much effort has been expended to develop heating and cooling systems that are energy efficient. In colder climates, energy conservation strategies, as well as alternative heating systems, have been developed.

Several management practices have proven very beneficial for greenhouse tomato seedling (young tomato plants that have not yet produced visible flowers) growers. Two of the most effective appear to be soil heating in conjunction with energy-saving thermal blankets. A properly managed greenhouse so equipped has resulted in nearly 60% reduction in fuel oil used per year.

Soil heating of a tomato seedling crop, for instance, speeds germination and seedling development and allows one to start the crop later than normal. This eliminates 2–3 weeks of operation during the coldest time of the year. Soil heating of low-growing crops also allows the night air temperature to be lowered about 3°C or more, further reducing energy requirements. In greenhouses with a floor heat storage system, because the floor mass is so large, there is a gradual decay in greenhouse air temperature throughout the night rather than the abrupt change that occurs in most greenhouses at sundown. In combination with a thermal blanket, the decline of the night air temperature is further slowed.

Extremely exciting possibilities exist in combining a floor heating system with low-temperature water typically rejected as waste heat from industrial sources. This system can be designed so that 34°C water can be used effectively to heat greenhouses. Cogeneration systems, that is, burning one fuel (e.g., natural gas or methane from landfills) to produce both heat and electricity, also offer benefits to the greenhouse operator.

From the standpoint of the engineer, systems can and have been designed to control temperature. But most of our information deals with heating, because most commercial greenhouse operations are active in areas that are too cold rather than too hot for field production. However, cooling and ventilating systems are a necessary and important part of the greenhouse design. Nonetheless, cooling in areas of high relative humidity and warm outside temperatures is accomplished only with prohibitive energy and capital costs. Most practical systems use shade, outside air movement through the greenhouse, and evaporation as the principal means of reducing excessive heat in the greenhouse. Solar radiation may cause the air that is moving through a greenhouse to raise 10°C or more as it travels from inlet to outlet. Even with the use of a traditional evaporative cooling system that consists of a porous pad down which water runs and through which the outside air is drawn, there are significant temperature gradients through a greenhouse. A more recent development has been evaporative cooling using a high-pressure fog system that sprays fine water droplets (0.02 cm diameter) evenly throughout the greenhouse. These droplets easily evaporate. Typically, one nozzle is placed every 5 m^2 with temperature reductions of 2–7°C depending on relative humidity.

The existence of these heating and cooling systems with the subsequent environmental control they provide has prompted commonsense questions such as: What temperature is best for plant growth? Should there be a differential day/night regime? Do all stages in the growth of a plant respond optimally to the same temperature? What about the environment of the root zone? To balance the desire for optimal plant growth with the efficient use of energy, these somewhat simple questions need to be accurately answered.

It appears that specific answers to heating and cooling needs are complex and depend on the genetic makeup of the plant, its physiological age, and previous environmental history. Some examples of the usefulness of root zone heating and the interaction of root zone and air temperatures on growth will illustrate the complex nature of temperature control and how it can be manipulated to provide an optimal product.

In-depth studies with tomatoes reveal a maximum growth plateau that slopes upward from about 16–30°C (Fig. 1). Above and below these points, significant growth retardation occurs. This graph illustrates a fairly general phenomenon that has led growers to develop rules of thumb for their greenhouse environmental control. Although the plateau for root zone temperature is fairly broad, it is quite obvious that certain temperatures are better than others for growth and that the cost of operation must be balanced against this growth response. However, the fact that precise information is needed before such decisions can be made is evident. Furthermore, an interaction between air and root zone temperature is shown in Figs. 2 and 3. These data suggest that increases in plant growth associated with root temperature increases may be due to some effect on the very early growth. The data show that the phase before rapid growth begins may be shortened by some increases in root temperature. Data collected during the rapid growth phase indicate that root temperature variation had little or no influence during that phase, which suggests that root temperature has a significant growth effect early in crop development. Once the root system is established, air temperature becomes more important for growth.

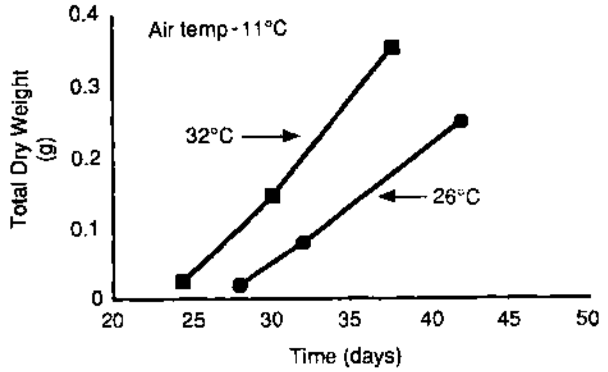

FIGURE 2 Plant dry weight as affected by growth at 11°C air temperature and root temperatures of 26 and 32°C. [From M. Mellata and H. W. Janes. (1987). Interrelation of root and shoot temperatures on dry matter accumulation and root growth in tomato seedling. *J. Hort. Sci.* **62,** 49–54.]

Maximum growth of tomato plants may be achieved only by maintaining air temperature at an optimal level. Low air temperature limits growth and growth rate even when root temperature is not low. Increases in root temperature do not increase growth response to an extent that can compensate for reductions in growth rate at low air temperatures. Root zone heating may be useful in optimizing growth at a given air temperature, especially if applied during

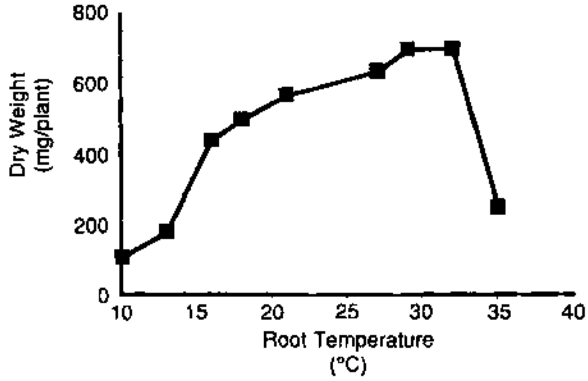

FIGURE 1 The effect of root zone heating for 2 weeks on the growth of tomato seedlings. [From J. Hurewitz and H. W. Janes. (1983). Effect of altering the root-zone temperature on growth, translocation, carbon exchange rate, and leaf starch accumulation in the tomato. *Plant Physiol.* **73,** 46–50.]

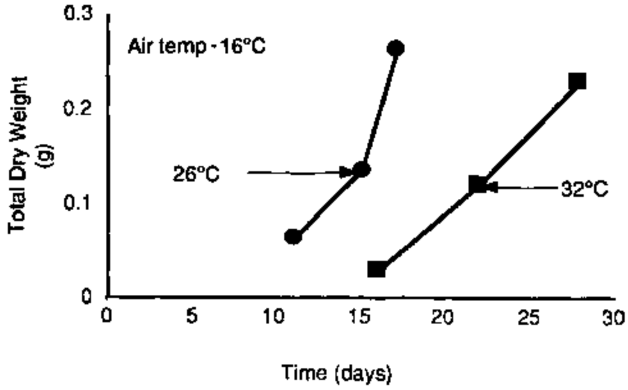

FIGURE 3 Plant dry weight as affected by growth at 16°C air temperature and root temperatures of 26 and 32°C. [From M. Mellata and H. W. Janes. (1987). Interrelation of root and shoot temperatures on dry matter accumulation and root growth in tomato seedling. *J. Hort. Sci.* **62,** 49–54.]

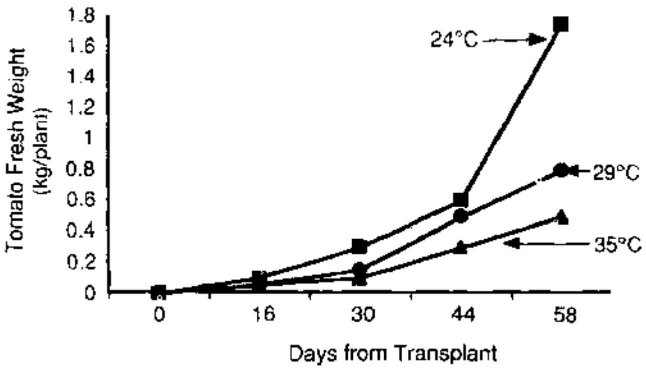

FIGURE 4 The effect of root zone heating on the accumulation of fresh weight by tomato plants following flowering. [From G. Giacomelli and H. W. Janes. (1986). The growth of greenhouse tomatoes in nutrient film at various nutrient solution temperatures. *Soilless Culture* **2,** 11–20.]

very early growth. High root temperature, however, may reduce growth rate, adversely affecting growth. The interrelationship of root and shoot activity ultimately determines the outcome of plant growth, so the temperature environment of each component is important. At extremes of hot or cold, either may have a critical effect on growth. However, when neither temperature is limiting, shoot temperature rather than root temperature appears to have the dominant effect on plant growth.

Within certain limits of air temperature (17–25°C), the optimal root zone temperature for tomato seedling growth is between 27 and 32°C. However, Figs. 4 and 5 show that prolonged growth at a root zone temperature of 29°C results in considerable decreases in both growth and crop productivity. There is a considerable difference in response to temperature depending on the age of the plant, its stage of physiological development, and the duration of a particular temperature treatment. It is clearly seen by looking at root metabolism (Fig. 6 and Table IV) that temperature has specific short- and long-term effects. Though promoting respiration and ATPase activity in the short term (30 min), a similar temperature inhibits these processes over the long term (7 days).

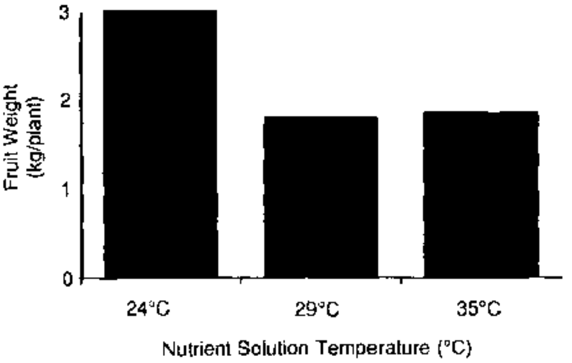

FIGURE 5 The effect of root zone heating on average marketable yields (fruit > 90 g) of tomato. [From G. Giacomelli and H. Janes. (1986). The growth of greenhouse tomatoes in nutrient film at various nutrient solution temperatures. *Soilless Culture* **2,** 11–20.]

The air temperature is of primary importance in the development of flowers following initiation. In particular, higher day temperature seems to be more effective in promoting growth than higher night temperature. Anthesis (flowering) can be delayed up to 18 days by giving temperatures of 10 versus 15°C for 14 days after floral initiation. In the winter under conditions of low irradiance, some floral abortion may occur under warm air temperatures (e.g., 21°C). Once the flower has developed, successful fertilization must occur to produce good-quality fruit. The germination of the pollen grain in tomato can also be affected by temperature. Generally it takes longer to germinate at lower temperature than at higher (5 hr at 10°C vs. 1 hr at 25°C). Germination must take place between 10 and 35°C. In the summer, short periods of time at 40°C without adequate ventilation will result in the failure of the egg to develop properly. Temperatures above 25°C at night and above 40°C during the day or below 10°C at night cause the most damage to greenhouse-grown tomatoes. It is recommended that night temperatures be in the range of 15–20°C (Table V).

The information presented here suggests that temperature regulation is a much more complex issue than it appears to be on initial reflection. The efficient operation of heating and cooling systems requires a thorough knowledge of the plant material and the desired end product.

TABLE IV

Length, ATPase Activity, and Respiration Rate of Isolated Tomato Roots Grown at Two Temperatures[a]

Temperature (°C)	Length (mm)	ATPase (μmoles P_i/mg protein/hr)	Respiration (μmoles O_2/min/m/g dry wt)
28	97	45.0	39
33	72	6.0	24

Source: H. W. Janes, C. Chin, and J. Bachmansky. (1988). Growth and metabolism of tomato roots grown in tissue cultures held at various temperatures. *Hort Science* **23,** 773.

[a] Roots were grown for 7 days at the temperatures indicated but ATPase and respiration measurements were made at 28°C. In each column, means are significantly different by LSD = 1%.

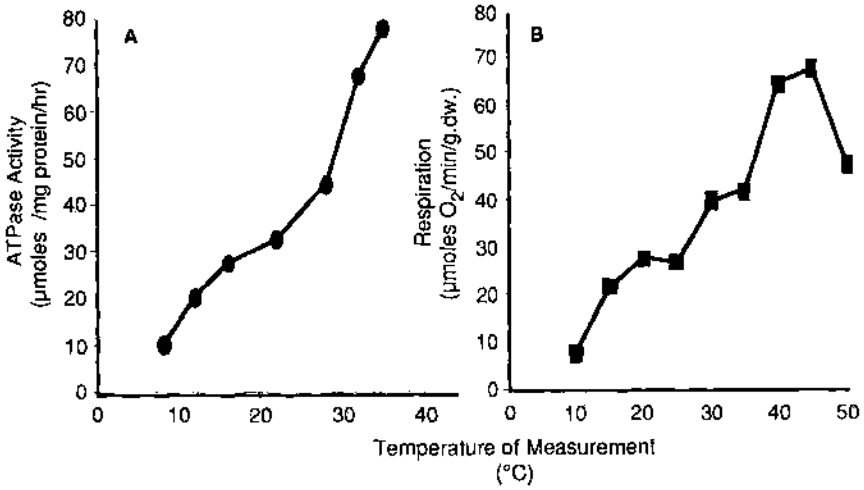

FIGURE 6 Respiration rate and K$^+$-stimulated ATPase activity as a function of assay temperature. Roots were grown for 7 days at 28°C and the measurements were made at various temperatures following 30 min of incubation of the roots at these temperatures. [From H. W. Janes, C. Chin, and J. Bachmansky. (1988). Growth and metabolism of tomato roots grown in tissue culture held at various temperatures. *HortScience* **23,** 773.]

TABLE V
Optimal Temperatures during Different Stages of Tomato Development

Stage	Temperature (°C)
Germination	16–29
Seedling growth	21–24
Fruit set	
Night	14–17
Day	19–24
Red color development	20–24

Source: J. G. Atherton and J. Rudich (eds.). (1986). "The Tomato Crop." Chapman & Hall, New York.

B. Light

Low winter light levels represent the single most limiting factor preventing continuous year-round production of greenhouse crops. Low light quantity is a major limiting environmental factor to plant growth for 6 months of the year in the Northern Hemisphere. This low light effect is exacerbated by a high incidence of cloud cover along coastal regions. Increasing fertility and better control of temperature, water, or CO$_2$ result in only marginal improvements in plant growth when light is limiting.

Because winter light is inadequate for production, tomato growers are unable to deviate from a spring–fall cropping strategy. Under winter light, only limited vegetative growth is possible. The production of vegetative crops such as lettuce in the Northern Hemisphere is greatly reduced in December and January, with the production time increasing from 6 to 10 weeks and total yields decreasing by 50%. Production of a reproductive crop, such as the tomato, is virtually arrested (Fig. 7). However, supplemental lighting in the greenhouse can be used to induce both photoperiodic and photosynthetic effects. Photosynthetic lighting can ease undesirable seasonal effects such as reduced flower production in tomato. Increases in flower number in response to both high intensities and long daylengths have been demonstrated. There is a linear relationship between total irradiance (400–700 nm) and the rate of seedling

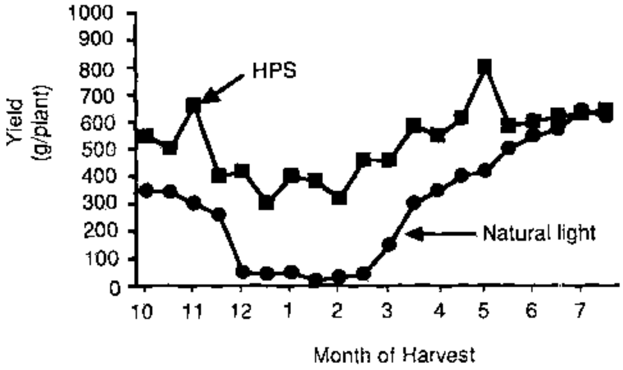

FIGURE 7 Comparison of the production of tomato plants grown with and without supplemental light. HPS lighting is used to supplement the natural radiation. [From R. McAvoy, H. W. Janes, B. Godfriaux, M. Secks, D. Duchai, and W. Wittman. (1989). The effect of total available photosynthetic photon flux on single truss tomato growth and production. *J. Hort. Sci.* **64,** 331–338.]

growth in both tomato and lettuce regardless of light source in the winter.

It was found in the 1940s that the growth rate and yield of certain tomato varieties increased as the number of hours of lighting increased. However, varietal differences are broad. Longer light periods may allow the grower to lower the greenhouse night temperature and save fuel dollars. By increasing the photoperiod to 16 hr there is a significant increase in growth and yield of tomatoes during November and December, and 16-hr photoperiods may allow a lowering of the night temperature. The intensity of the supplementary light is extremely critical. If the normal daylight is extended with high-intensity light, the growth and yield of the plants are enhanced. However, if low-intensity supplemental light is used, the flowering can be delayed.

The same total light intensity given over 8 or 16 hr can dramatically alter tomato growth. A 16-hr day results in an increased net assimilation rate as well as higher chlorophyll levels. However, flowers appeared one or two nodes lower on plants given only 8-hr days. The faster growth rates under 16-hr days would more than balance out the faster flowering with 8-hr days and result in higher yields. In England in midwinter, day lengths of less than 6 hr result in absolutely no growth and that growth is proportional, at this time of year, to light intensity or duration.

Lighting during November and December will cause flowering to occur 10–14 days earlier than normal, which translates into an increase of 4.7 tons of fruit per acre over the life of the crop. Furthermore, with increased lighting in the winter, the number of misshapen fruit declines. Also, color development and fruit quality, as measured by taste panels, are enhanced by supplementary lighting.

Research in this area can become extremely complicated owing to the interaction between lighting and various other environmental and physiological conditions. An experiment run for 1 week may give you one answer and that for 2 weeks another answer. Table VI illustrates the problem. If the same amount of supplemental light is given for a 33-day period during tomato seedling growth, with high light being provided in one of the three 11-day periods, the end result is quite different depending on which period received the high light. Vegetative plant growth responded differentially to the total light integral, depending on when it was applied during the growth cycle. However, for the production of a tomato crop it is best to provide light earlier in development rather than later.

TABLE VI

The Influence of an 11-day High-Light Treatment Applied Differentially during Seedling Development on Vegetative Growth[a]

Growth variable	Light treatment	Sampling date Day 6	Day 11	Day 22	Day 33
Total dry weight (g)	HLL	0.05b[b]	0.32b	3.53b	14.27a
	LHL	0.02a	0.12a	4.47b	13.92a
	LLH	0.02a	0.11a	2.31a	19.44b
Leaf area index (cm²)	HLL	0.06b	0.32b	2.41b	3.04a
	LHL	0.03a	0.16a	2.32ab	2.95a
	LLH	0.03a	0.16a	1.82a	3.38a
Leaf area ratio (cm²/g)	HHL	276a	249a	254b	195b
	LHL	408b	356b	188a	192b
	LLH	446b	360b	298b	158a
Plant height (cm)	HLL	0	6.1b	32.7b	75.3b
	LHL	0	4.2a	26.8a	63.9a
	LLH	0	4.1a	29.3ab	66.8a

Source: R. McAvoy and H. Janes. (1990). Cumulative light effects on growth and flowering of tomato seedlings. *J. Am. Soc. Hort. Sci.* **115,** 119–122.

[a] Each number is the mean of 15 plants.

[b] Data followed by different letters indicate significant differences between light treatments on a certain sampling date at the 5% level as determined by Duncan's multiple range test.

Additionally, the interaction between supplementary lighting and seasonal changes in night temperatures deserves some mention. Both leaf formation and growth increase with both light intensity and temperature. However, an increase in temperature also meant an increased number of nodes prior to floral initiation. Whether increased growth rates under warmer temperature regimes with supplementary lighting will offset the delay in flowering remains to be seen. This will play an important role in the timing of a crop.

The effects that light has on plant growth are not limited to its involvement in the photosynthetic process. There are numerous examples of the action of light (duration and quality) on growth, flowering, and plant hormone activity. It would be a mistake to assume that by changing the photoperiod one was only altering the rate of sugar formation. For tomato, the length of the light period has little effect on flowering, that is, tomatoes are day-neutral plants. However, there is some evidence to suggest that some tomato cultivars are quantitative short-day plants. By increasing the length of the day with low levels of incandescent light, the number of leaves below the first inflorescence can be increased, but the plant will still flower. Additionally, daylight–dark cycles that deviated too greatly from a 24-hr cycle of 12 hr light and 12 hr darkness were inhibitory to plant growth. In a 48-hr period if all the plants received the same

TABLE VII

Growth of Tomato in Different Durations of Light with Equal Total Light[a]

Light regime	Leaf area	Dry weight leaves	Fresh weight stems	Dry weight stems
18 hr 200 μE/m^2/sec 6 hr dark (control)	100.0	100.0	100.0	100.0
24 hr 150 μE/m^2/sec	59.8	40.1	66.0	65.8

Source: F. Bradley and H. W. Janes. (1985). Carbon partitioning in tomato leaves exposed to continuous light. *Acta Horticulturae* **174,** 293–302.

[a] In each column, values are not significantly different at $P \leq 0.05$. Values represent the average of five plants per treatment, expressed as percentage of control.

quality and quantity of light in alternating light–dark cycles of 6, 12, o4 24 hr, the tomatoes grown under 6- and 24-hr light regimes exhibited growth inhibition. It is clear that with tomato seedlings, equal light intensity given over 18 or 24 hr results in different plant growth rates (Table VII). [*See* PHOTOSYNTHESIS; PLANT PHYSIOLOGY.]

Photosynthetic period has also been found to affect carbon export in tomato. Translocation and partitioning of carbohydrate was altered by the duration of the photosynthetic period or possibly by the duration of the dark period rather than the absolute light intensity. More sugar is translocated out of the leaves under a 16-hr photoperiod than under an 8-hr photoperiod, even when the total amount of carbon fixed in photosynthesis is the same (Table VIII).

The interactions of photomorphogenic factors controlling sugar export and its partitioning within the plant need to be seriously addressed, as they are directly related to crop yield. Photomorphogenic effects are known to modify the distribution of photosynthesis products. This may have significance for artificial lighting, as the spectral pattern of certain popular light sources is deficient in blue light and heavy in the near infrared region relative to sunlight, and so photomorphogenic changes are probable.

TABLE VIII

The Light Period Effect on Carbohydrate Movement Out of the Leaf (Translocation)[a]

Length of light period (hr)	Photosynthetic rate (g CH$_2$O/m^{-2}/hr)	Total carbohydrate fixed daily (g/m^{-2})	Total carbohydrate translocated daily (g/m^{-2})
8	0.74b	5.95a	3.46a
16	0.37a	5.87a	4.88b

Source: S. Logendra and H. W. Janes (1992). Light duration effects on carbon partitioning and translocation in tomato. *Scientia Horticulturae* **52,** 19–25.

[a] Values in columns followed by the same letter are not significantly different at $P < 0.05$.

Selection of a light source is not easy given the various types available. One of the most common light sources is the fluorescent lamp; however, it is not practical for commercial application. The practical use of the fluorescent source is limited by its unwieldy size, its low-intensity discharge, and safety regulations requiring moisture barriers to protect the bulb in the wet greenhouse. The high-pressure sodium (HPS) light source is an attractive source for commercial use. The fixture is fairly compact and the bulb has a life of up to 20,000 hr. The HPS lamp is the most efficient, after the low-pressure sodium lamp, in terms of the percentage of the total input energy, which is converted to visible light. With the HPS lamp 25% of the total input energy is emitted as visible light. Metal halides range from 12 to 20%; fluorescent lamps are 20% efficient in this conversion. The low-pressure sodium (LPS) lamp has a 27% efficiency. The LPS lamp, a monochromatic light source, has a short bulb life, and the fixture is also much larger than that of the HPS lamp. Considering all factors—ballast and fixture size, safety, energy conversion efficiency, spectral distribution, and bulb life—the HPS lamp is the most commercially applicable of the available light sources for supplemental lighting in the greenhouse.

Spectral distribution of any artificial light source is always a concern because the sunlight spectrum is never completely reproduced by any single light source. The discrepancy between an artificial light source spectrum and the solar spectrum is significant as light quality has been shown to influence plant growth and development. Table IX shows that add-

TABLE IX

Light Quality Effect on Tomato Response to Continuous Light[a]

Continuous light treatment	Chlorophyll (mg/gfw)	Starch (% DW)	Leaf death (#/plant)
Fluorescent	0.22	4.46	2.83
Fluorescent + far-red	0.49	7.17	1.17

Source: S. Globig, I. Rosen, and H. W. Janes. (1994). Continuous light effects on photosynthesis and carbon metabolism. *Acta Horticulturae*.

[a] In each column, values are not significantly different at $P < 0.05$.

ing far-red light (730 nm) to fluorescent light provided to tomatoes on a continuous basis can delay leaf death and alter starch levels.

We also need to know the optimum ratio of the various wavelength intervals, particularly in the blue, red, and far-red regions. This can be illustrated by considering the response of flowering in tomato under cool white fluorescent lights or fluorescent lights and incandescent lamps. In the latter case, the plant receives more far-red light and the time to first flower opening is reduced by 2 days.

A caution needs to be issued here regarding supplemental lighting for tomatoes. Continuous light can result in severe damage with significant decreases in growth and possibly death of the plant (Table VII). It is recommended that at least a 6-hr dark period be provided. Seedlings will be more quickly affected by continuous light than older plants. Also, reducing the "night" temperature in comparison to the "day" will delay the injury appearance. Older leaves of injured plants will lose chlorophyll and turn yellow, and young leaves will not develop chlorophyll and will appear white. Obviously, photosynthesis is decreased and a reduction of growth results. If the continuous light is not stopped, the plant can die.

C. Carbon Dioxide

The use of CO_2 enrichment in the greenhouse has taken on added significance in recent years. With the advent of energy-conserving techniques to prevent heat loss from greenhouses, they are now sealed better and much tighter to outside airflow. Although energy is saved, the CO_2 levels can dramatically decrease when plants are photosynthesizing in a closed greenhouse. This problem is particularly acute during clear, cold days when photosynthetic levels may be high and air exchange between the interior of the greenhouse and outside air is small. Also, the use of supplementary lighting at night makes CO_2 enrichment even more necessary as depletion of the CO_2 concentration will result in dramatic decreases in photosynthesis and plant growth while wasting the energy spent on lighting. Increased levels of CO_2, possibly as a consequence of promoting overall plant growth, will also speed up the date for first flowering in tomato. It is likely that increases in fruit production to CO_2 enrichment in the winter are largely the result of more flowers reaching maturity.

In tomato, levels of CO_2 between 1000 and 1500 μl/liter of air provide adequate substrate to maintain high photosynthetic rates as well as increased translocation of carbohydrate out of the leaves, resulting in increased whole-plant growth. However, CO_2 concentrations above 5000 μl/liter can be dangerous to both humans and plants. Though CO_2 injection should be practiced, too much of a good thing can cause trouble. CO_2 can be added to the greenhouse from a supply of liquid CO_2 that is distributed throughout the greenhouse via a fan-tube system. This is the cleanest way of adding CO_2. The most prevalent way of producing CO_2 is by suspending an open-flame burner in the greenhouse; generally, propane or natural gas is burned. These burners can be controlled by commercially available computerized systems that can monitor and regulate CO_2 levels. The burners have an advantage of adding some heat to the greenhouse. When using CO_2 generated by burning propane or other fuels in the greenhouse, however, it is possible that production of volatile pollutants such as ethylene, propylene, and oxides of nitrogen and sulfur may occur. At first glance, CO_2 enrichment appears to be a positive process that should be practiced by greenhouse operators, because it is clearly associated with increased rates of photosynthesis and plant dry matter accumulation. However, there appear to be long-term and short-term effects of high CO_2 concentration on tomatoes, with increased photosynthetic rates not persisting over long time periods (Fig. 8).

To complicate matters further, the nitrogen fertilizer status of the plant can influence the amount of carbohydrate translocated out of the leaf following exposure to high CO_2 levels. This points out the fact that, as with light and temperature, the response to above ambient CO_2 levels for long or short periods of time needs to be studied prior to deciding (1) how to most efficiently apply this material and (2) whether

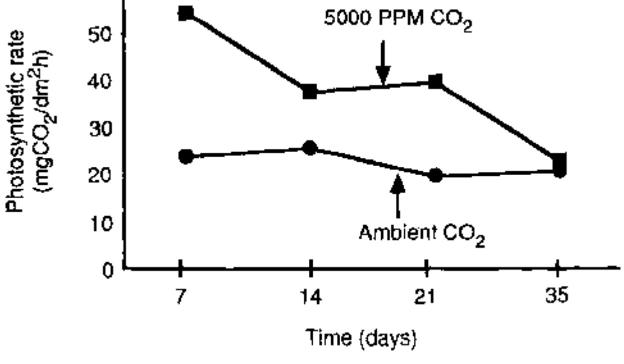

FIGURE 8 The effect of high carbon dioxide on photosynthesis of whole tomato seedlings.

or not long exposure to CO_2 above ambient levels is warranted.

Before concluding our discussion of CO_2, it should be mentioned that companies in Europe are marketing equipment that will add CO_2 to the irrigation water. They contend that CO_2 benefits root growth as well as photosynthesis. In tomato seedlings it would appear that short-term exposure of the roots (less than 12 hr) to high concentrations of CO_2 will result in increased whole-plant growth (Fig. 9), however, high CO_2 levels and/or long durations can limit growth. These CO_2 effects are due not to increased photosynthesis, but possibly to a more specific effect of CO_2 on nutrient uptake by the plant roots.

D. Humidity

The amount of water in the air plays a significant role in plant health. Too much water can lead to the proliferation of disease-causing organisms and result in the inability of pollen to be released and move to the stigma. High humidity is a concern in some greenhouses because measures taken to conserve heat also serve to raise the relative humidity. Under high light levels, raising the relative humidity to about 90% was shown to actually increase growth. The growth of young tomato seedlings may be accelerated by enhanced CO_2 assimilation resulting from the increased number of open stomates at higher humidity. However, humidity seems to have much less of an effect on tomato growth and development than do light, temperature, CO_2, or nutrients. Additionally, the uptake and distribution of certain nutrients like calcium can be seriously affected by the relative humidity of the greenhouse. Young leaves will have low calcium levels if the humidity is high (95%), whereas fruit will have low calcium levels if the night humidity is below 50%. This is due to the method of calcium transport into these different organs. Leaves receive calcium as a result of transpiration (evaporation of water from stomates), whereas the fruit relies on root pressure to supply calcium. The lack of calcium in the ovary and young fruit can result in a serious condition called blossom end rot. Fruit with this physiological disorder are unsalable.

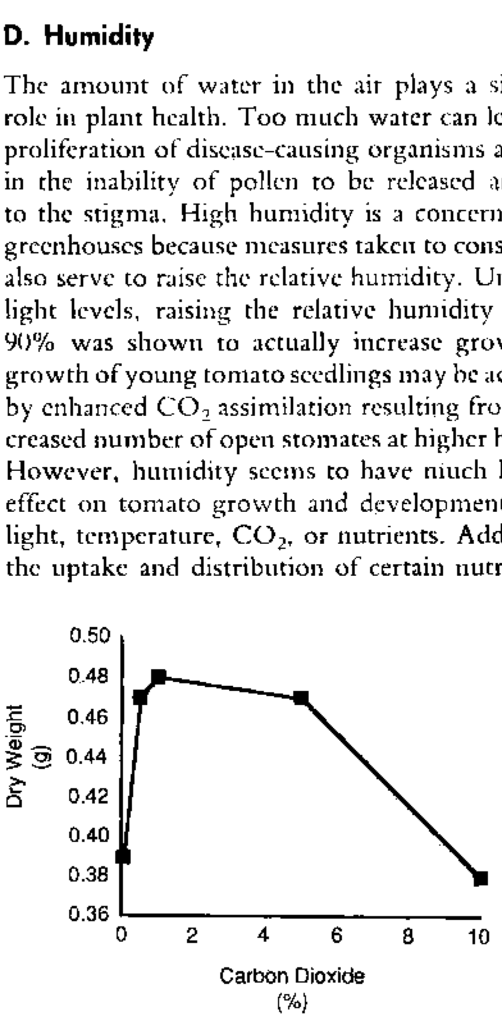

FIGURE 9 The effect of carbon dioxide concentrations (0.03, 0.5, 1, 5, and 10%) on the dry weight growth of tomato leaves. The root systems of 5-week-old tomato plants were treated for 12 hr with CO_2. [From Yurgalevitch and H. Janes. (1988). Carbon dioxide enrichment of the root zone of tomato seedlings. *J. Hort. Sci.* **63,** 265–270.]

E. Nutrition

In controlled environment culture, the commercial production of tomatoes is done using some type of soilless growing method. Usually either a form of hydroponic culture called the nutrient film technique (NFT) or a nonsoil growing media is used. Current popular nonsoil media are rockwool and a mixture of peat moss, vermiculite, and perlite (referred to as a peat-lite mix). Rockwool is manufactured from crushed rock heated to over 600°C. The molten material is lengthened into strands that are pressed and cut into a variety of shapes and sizes. These systems have replaced natural soil for several reasons, most significant being the expenditures of energy, particularly the labor cost needed to transport and sterilize soil. Additionally, the replacement of soil with soil of equal quality is difficult. NFT, rockwool, and to some extent peat-lite mixes provide a grower with constant quality year-in and year-out without the need to initially sterilize to remove weed seeds, fungi, insects, and bacteria. Furthermore, soilless culture allows easier manipulation of the environment and the ability to provide the proper nutrients for healthy tomato growth.

An in-depth discussion of tomato nutrition will not be given here. However, Tables X and XI show the nutrient levels recommended for tomato and provide some generalized descriptions of deficiency symptoms. The reader is cautioned that providing fertilizer above optimum levels will result in growth inhibition. It should also be a goal to provide the plant with no more than necessary, which saves dollars on fertilizer but also protects the environment. Frequent overwatering or disposal of nutrient solution in an NFT system will result in higher fertilizer levels leaching into the ground-water, which can lead to the overproduction of algae and other microorganisms. Every effort should be made to collect and recycle

TABLE X

Optimal Nutrient Levels in the Fertilizer Solution for a Tomato Crop

Element	Concentration (ppm)[a]
Nitrate-nitrogen (NO_3-N)	150–200
Phosphorous (P)	50
Potassium (K)	200–400 [P_2O_5 = 1140]
Calcium (Ca)	150–300 [K_2O = 240–480]
Magnesium (Mg)	50
Iron (Fe)	5
Manganese (Mn)	1
Copper (Cu)	0.1
Zinc (Zn)	0.1
Boron (B)	0.2
Molybdenum (Mo)	0.05

Source: H. M. Resh. (1989). "Hydroponic Food Production." Woodbridge Press, Santa Barbara, CA.

[a] 1 ppm = 1 oz. per 7500 gallons.

the nutrient solution. The solution will need to be frequently tested to make sure the proper nutrient levels are maintained. Additionally, the pH should be maintained between 5.5 and 6.0. Probably the greatest threat faced by the grower in recycling nutrients is the spread of disease. The nutrients used by the plant for good growth are also those required by many microorganisms. If you add to the solution the organic material from plant decay and exudation, you have created a media for the growth of many organisms. Today no cost-effective and totally satisfactory resterilization system exists. However, methods such as ultrafiltration, ultrasonics, heat treatment, UV irradiation, and ozone treatment have been tried, with the latter two showing the most promise.

TABLE XI

Nutrient Deficiency Symptoms in Tomato

Element	Symptom description
Nitrogen	Plants are light green (lack chlorophyll); younger leaves may remain green longer
Potassium	Older leaves develop symptoms first and become chlorotic (i.e., lose their green color) and soon develop scattered dead spots
Phosphorous	Leaves are dark green; purple pigmentation may develop; growth rate slowed and the plants appear stunted
Calcium	Shoot tip growth slows and root tips may die; young leaves exhibit scattered dead spots; these leaves are generally small with twisted tips
Manganese	Leaves become chlorotic but the veins remain green (interveinal chlorosis); dead spots develop on the leaves with some leaves falling from the plant
Magnesium	Older leaves develop interveinal chlorosis; leaf margins may curl
Iron	Interveinal chlorosis, similar to with magnesium deficiency except on the younger leaves; edges and the tips of leaves may die

Source: H. M. Resh (1989). "Hydroponic Food Production." Woodbridge Press, Santa Barbara, CA.

III. Tomato Cropping Systems

Greenhouse tomatoes are typically produced on multiple-trussed vertical vines. In these systems, plant densities of about 10,000–12,000 plants/acre are common. Plants are placed in double rows 40–45 cm apart with plants 30–35 cm apart within the row. Usually the plants are staggered in adjacent rows. Tomatoes can be trained vertically by clamping to a string hung from a wire stretched across the greenhouse. Tomatoes are always pruned to a single stem, with lateral branches being constantly removed. When the plants start setting fruit on the third cluster, it is beneficial to start removing the lower leaves to improve aeration and remove possible material for disease organisms to infect. Also the fruit will not set without pollination. In the greenhouse this is accomplished either by mechanical vibration of the flower cluster or by bringing bees into the greenhouse.

In the United States and Canada, tomato production follows a two-crop pattern. The spring crop is seeded between December 1 and January 15 and harvested starting in late April through July. The fall crop is seeded between July 1 and 15 with a harvest window commencing in October and ending in late December. Primarily because of low light levels, the yields in the fall are up to 50% less than those in the spring. Crop production ceases during the low-light winter months, as the old crop is terminated and new plants take their place.

Market demands place a premium on the continuous and predictable production of quality fruit. However, under constantly changing environmental conditions, continuous and predictable production of tomato fruit is difficult to accomplish. When uniform fruit quality is desired, this task becomes even more difficult to achieve.

Continuity of production during the winter months is important because the potential financial returns are highest at this time. Winter tomato production is expensive, however, and low light intensities combined with short days drastically reduce crop performance and quality. Supplementing the naturally available light with artificial light will alleviate some of these problems but supplemental lighting is expensive. Therefore, utilizing this resource to achieve the maximum benefit with a minimal investment is an important consideration. Adding supplemental light to a vertically grown tomato crop (the traditional cultural method) has two disadvantages: (1) light uniformity is difficult to maintain and (2) it is impossible to tailor the supplemental light schedule to a specific stage of crop development. Because many stages of plant growth and development occur simultaneously, light can not be used judiciously to achieve a specific growth effect.

A single-cluster tomato production system is capable of continuous tomato production. This system is not limited by the disadvantages inherent to vertical axis cropping systems when supplemental lighting is used. The basic components of the Rutgers version of the single-cluster production system include single-cluster tomato plants, transportable benches (tables upon which plants are grown and transported), high-pressure sodium lights, and a crop management strategy based on a plant growth model.

In this system the tomato plant is pruned to a single flower cluster and architectured by soft pinching the apical meristem one leaf above the cluster. High plant populations, 43,000 plants/acre compared to more conventional densities, are used to ensure maximum yield and to enhance crop uniformity. The high plant population concentrates crop maturity into a narrow time period, or production window. Sequential cropping of discrete groups of plants on a staggered time schedule results in continuous production. Transportable tables increase space utilization and predispose the crop to further automation and improved labor efficiency by facilitating the flow of materials in and out of the production house.

TABLE XII

Greenhouse Cost Accounting

Overhead	Utilities	Wages and salaries	Direct costs
Depreciation	Heating fuel	General	Seeds
Interest	Telephone	FICA	Pots
Repairs	Electricity	Unemployment insurance	Media
Taxes	Water	Workmen's compensation	Fertilizer
Insurance			Tags
Advertising			Others
Office expenses			
Professional fee			
Truck expense			
Equipment rental			
Dues			
Bad debts			
Miscellaneous			

Buildings and utilities	Equipment
Land	Heating system—Piping
Site grading and roads	Boilers—gas, 2
Site services, utilities	Boiler controls
Service building, structure	Heating system—installation
Service building, internal	Supplemental lighting
Greenhouse—structure	Supplemental lighting
Greenhouse– installation	Electrical–internal
Concrete paths	Electrical—service
Contingency—10%	Shade system/thermal blankets
	Blackout curtains
	Air handling
	Carbon dioxide system
	Crop support system
	Growing system
	Nutrient system
	Computer controls
	Vehicles, tools, etc.
	Grading and packaging equipment

Source: R. Brumfeld, P. Nelson, A. Coutu, D. Willits, and R. Sowell, (1981). "Overhead Costs of Greenhouse Firms Differentiated by Size of Firm and Market Channel." Technical Bulletin 269. North Carolina Agricultural Research Service, Raleigh.

Tomatoes are one of the least automated of the greenhouse crops. Commercial mechanization of the conventional vertical axis tomato crop has been limited to systems where the machinery has been adapted to the crop. The single-cluster production system adapts the tomato crop to existing machinery and market requirements by modifying cultural practices such as plant density and plant architecture, as well as operational practices such as crop accessibility, handling, and scheduling. Thus, precision seeders, potting machines, soil mixers, pot fillers, and pot transfer mechanisms that place pots on movable benches, conventionally used for small pot crop production (e.g., poinsettia or mum production), can be applied to the tomato crop. The single-cluster tomato crop, like the pot crop, offers a high degree of uniformity and is small, compact, and easy to handle.

The concept of growing single-cluster tomatoes for the purpose of reducing labor and developing a factorylike production scheme is the aim of the Rutgers single-cluster production system. By applying the information presented here for the control of tomato growth by environmental manipulation it seems possible that a plant factory production system could become a reality for tomatoes.

IV. Economic Considerations

In many cases, greenhouse producers of tomatoes owe their success or failure to the managerial choices they make as opposed to the technical choices. As we have seen, the technical choices of which temperature, light level, or growing media to use are complicated. The same can be said for the managerial choices. Greenhouse managers need to know their fixed "overhead" costs and their costs of production to effectively analyze alternative possibilities, implement choices, and evaluate courses of action.

No attempt will be made here to provide a methodology for a detailed economic analysis or feasibility of a greenhouse tomato business. Table XII provides the reader with a general idea of what must be considered when computing the profitability of a tomato greenhouse production business.

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Transgenic Animals

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Glossary

Cloning Process of isolating and reproducing the DNA carrying a gene's nucleic acid sequence
Gene Sequence of DNA that specifies a unit of function, including the structural information for the gene product as well as the regulatory sequences controlling expression
Gene expression Production of the product of a gene; genes exert their effect through products, usually proteins; without expression, the organism would look as though the gene were not present
Genetic recombination Classically, the reassortment of genetic traits during formation of the gametes in sexual reproduction; for example, crosses between hornless black cattle and horned red cattle might produce the new combination of traits, hornless red animals; genes can now be recombined chemically in a process referred to as recombinant DNA techniques or "genetic engineering"
Genome Entire genetic complement of an organism
Transgene Gene introduced into an organism using recombinant DNA techniques

Transgenic animals are animals with a gene or a genetic sequence produced using recombinant-DNA techniques. The gene may be in somatic tissues only or may become part of the germ line. Transgenic animals are useful for numerous scientific purposes including the study of development, physiology, genetics, and human diseases. Agriculturally, they show promise for enhancing animal productivity and food quality.

I. Introduction

A. Definition of Transgenic Animal

It is now possible to introduce virtually any desired genetic sequence into the genome of an animal. The introduced sequence or transgene becomes part of the germ line, and the recipients of such sequences are called transgenic animals. Genes can also be introduced into somatic tissues where they may or may not be integrated into the genome. Such animals are also considered transgenic, although the transgene would not be transmitted to progeny.

Recombinant DNA techniques or "genetic engineering" make the transfer of genes across traditional species lines possible. Gene transfers can be made between animal species or from the plant kingdom into the animal kingdom, or a totally synthetic gene can be introduced into an animal. However, transgenic does not necessarily imply that the transgene is from a different genus.

B. How Transgenic Animals Are Made

In animals, gene transfer is accomplished by cloning the desired gene, usually followed by injection of the cloned DNA into a fertilized ovum or zygote. This is illustrated in Fig. 1. The round structure shown in the center of the figure is a fertilized swine ovum. The large pipette at the right is attached to a vacuum line to hold the ovum in place. The thin pipette inserted at the left of the ovum contains a solution of the cloned gene and is injecting copies of the gene into a pronucleus of the ovum. Both the paternal and maternal pronuclei are seen in the center of the ovum. The paternal and maternal genetic material will coalesce, and in a small percentage of the cases, a copy of the cloned gene will become a part of the animal's genome. Genes integrated into the genome usually replicate whenever the chromosome replicates, be-

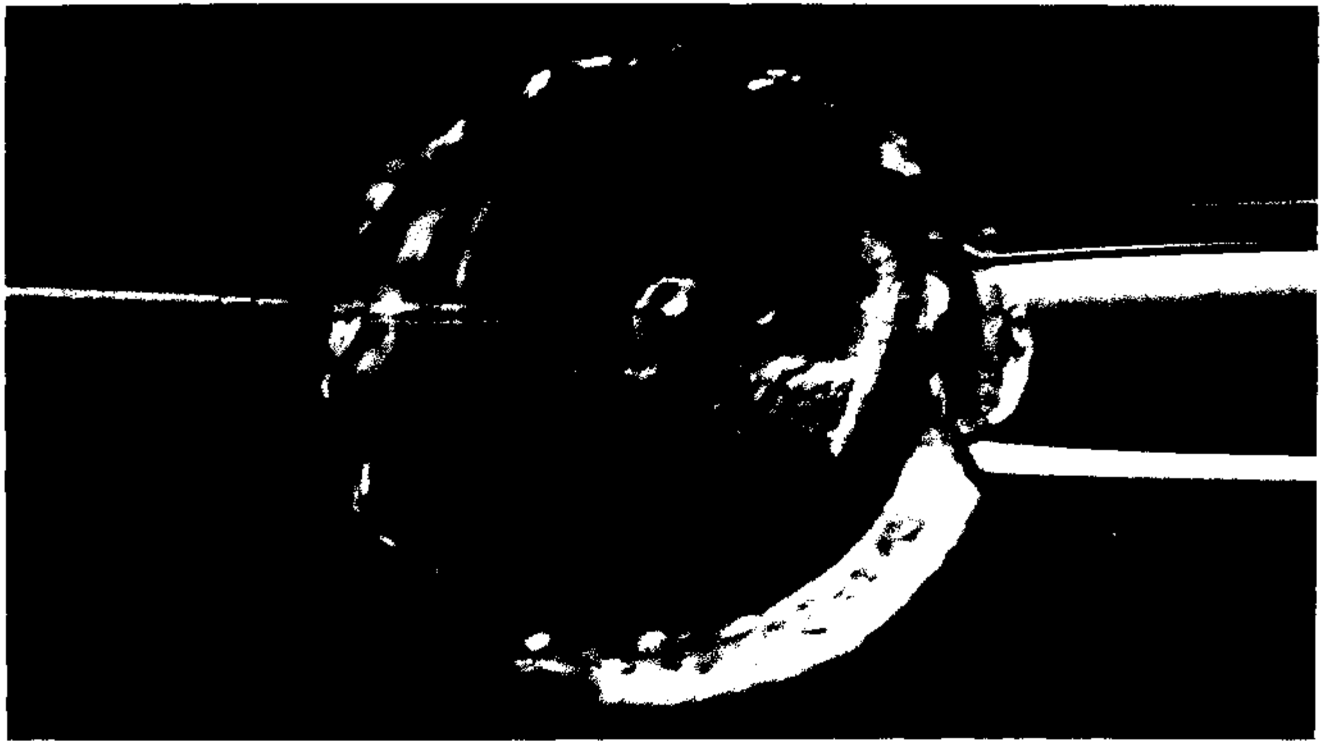

FIGURE 1 A fertilized swine ovum (zygote). The zygote has been centrifuged to make the maternal and paternal pronuclei visible for injection. The dark material separated by centrifugation is on the bottom of the zygote. [The picture was taken by R. E. Hammer and R. L. Brinster. Reproduced with permission from R. E. Hammer, V. G. Pursel, C. E. Rexroad, Jr., R. J. Wall, D. J. Bolt, K. M. Ebert, R. J. Palmiter, and R. L. Brinster. (1985). *Nature* **315,** 680–683.]

having as any other gene in the animal. In most cases the injected gene does not integrate into the recipient genome and is probably degraded. For this and other reasons, not more than 1 to 5% of the mouse zygotes injected develop into transgenic animals. The production of transgenic agricultural animals is even less efficient, ranging from 0.1 to about 0.5% of the injected zygotes.

C. Uses of Transgenic Animals

The applications of transgenesis are many, ranging from the use of short-unique DNA sequences as identity markers in animal lines, to the introduction of transgenes expected to result in more efficient animal productivity as measured by a reduction in the feed to gain ratio or in faster growth. Agricultural productivity may be enhanced by introducing genes for disease resistance or for the extension of the ecological range. For example, the ecological range may be extended into colder water for some species of fish. Many species of fish produce antifreeze proteins that lower their freezing points, allowing the fish to survive in colder water, but the introduction of antifreeze protein genes into additional fish species will allow these fishes to extend their ecological ranges. Nutritional enhancements may be possible by the introduction of genes causing, e.g., increased proportions of unsaturated fatty acids or decreased quantities of total fat. The agricultural applications of transgenesis are discussed in more detail below.

Transgenesis has a wide range of medical applications. Several of the traditional agricultural species are being used as "pharm animals" to produce drugs. Because some therapeutic agents are naturally occurring proteins or polypeptides, scientists can link the genes for these drugs to a regulatory sequence specifying expression in a specific tissue such as the mammary gland. The milk then becomes a source of a large quantity of drug which is relatively easy to isolate. The safety advantage is even more important than the simplified isolation. The harvesting of drugs from human tissue inherently brings with it the danger of transmitting human diseases through the drug. The transmission of AIDS to children receiving blood-clotting factors isolated from human serum is an example. The isolation of human proteins from transgenic animals makes the transmission of human infections far less likely. Transgenesis will also be used to produce animal tissues and organs suitable for transplantation to humans. Human organs for transplantation are in very short supply, so the objective is to genetically alter the animal tissue to reduce or eliminate rejection reactions, increasing the availability of tissues and organs suitable for transplantation. As with the drugs discussed above, this would also reduce the possibility of disease transmission from transplants.

Transgenic animals are proving to be very useful as models of human diseases. The "Harvard mouse," the first transgenic animal to be patented, is missing a tumor suppressor gene and develops tumors. The mouse is useful for studying cancer. A second Harvard mouse has recently been patented and is useful for studying benign prostatic hypertrophy, a common disease in older males. The mouse carries a growth factor gene with a controlling region assuring that the gene is expressed only in the prostate. This will be useful for detecting carcinogens and for studying treatments for prostatic hypertrophy.

In principle, once a gene for any hereditary human disease is identified, animal models can be generated by introducing the defective gene into an animal or simply by using gene targeting (see below) to disrupt the normal gene. The recipient animal is selected on the basis of a compromise between the ease of experimentation and the physiological similarity to humans for the purpose of studying the progression of and potential treatments for the disease. For instance, a gene for sickle cell anemia has been introduced into a mouse, and the mouse line is now being used to compare alternative treatments for the anemia. Two potential treatments are being evaluated. One is to coat the red cells with a chemical that helps them slip through blood clots. The other is to induce the expression of the fetal hemoglobin gene, a gene usually turned off after birth. Fetal hemoglobin could carry oxygen and dilute out the sickle hemoglobin. Transgenic animal models will be useful for comparing the effectiveness of treatments.

In addition to treating diseases, transgenesis also offers opportunities for preventing disease. Scientists are attempting to introduce transgenes that would prevent parasites from entering or maturing in intermediate hosts, thus interrupting the life cycle of the parasites. World wide, malaria kills about a million children a year. Insecticides are becoming less effective against the mosquito, the intermediate host, so transgenesis may offer an important alternative for controlling the disease by preventing pathogen production by the mosquito. Similar experiments are being conducted on snails, intermediate hosts for schistosomiasis.

II. The Production of Transgenic Animals

The introduction of a new gene into an animal requires a large amount of the gene in pure form. This is achieved by cloning, the process of isolating and culturing a gene to produce the needed quantity in pure form. A brief overview of some pertinent principles of molecular biology and cloning follows. The objective is to explain some basic principles with only enough technical details to make the concepts clear. Additional details can be found in the materials referenced.

A. Molecular Biology Background

The sequence of nucleotide bases in DNA contains the genetic information. Each position in the DNA is occupied by one of four bases, adenine (A), guanine (G), cytosine (C), or thymine (T), and each is chemically linked to the previous and next base in the strand by sugar–phosphate bridges. (see gene segment in Fig. 2.) The two strands of the DNA double helix are held together by hydrogen bonds between the bases. The geometry of the hydrogen-bonding groups in the bases is such that adenine always pairs with thymine, and guanine with cytosine, so the base sequence of the initial strand automatically determines the sequence of the complementary strand.

Most genes code for proteins, and proteins are uniquely determined by their amino acid sequences. Each sequence of three DNA bases codes for an amino acid, so the sequence of nucleotide bases in DNA dictates the amino acid sequence in proteins. Some three-base sequences determine the punctuation, coding for starting or terminating the formation of the protein chain.

DNA is not "translated" into protein directly, but first produces a messenger ribonucleic acid (mRNA) which leaves the nucleus of the cell and enters the cytoplasm where translation takes place. The mRNA has the same sequence as the coding strand of DNA, but uracil (U) replaces T. The formation of mRNA is called transcription. The reading of the messenger RNA three bases at a time, translation, produces the protein specified by the gene. Gene expression refers to the production of the gene product from the gene. The rate of production of protein is regulated at the transcription, translation, and post-translational levels, but the rate of transcription is a direct assessment of the control of expression at the gene (DNA) level.

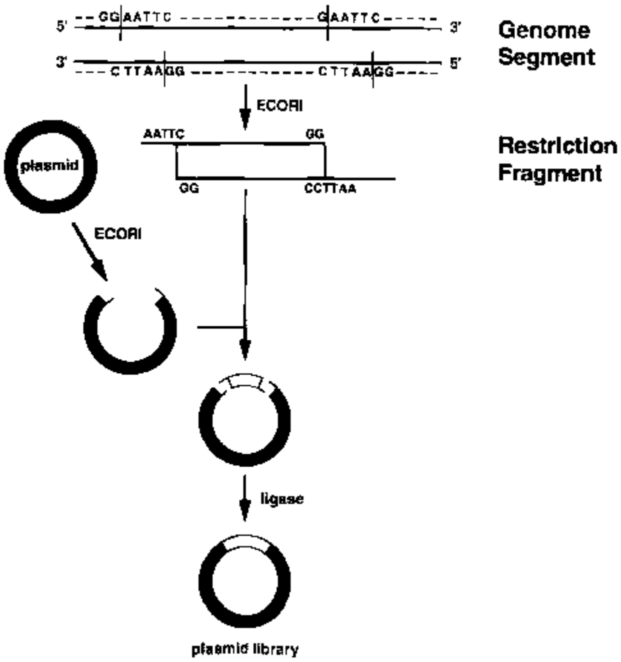

FIGURE 2 The genome segment at the top of the figure shows a DNA double helix with its two complementary strands. The two strands are held together by hydrogen bonds between the complementary base pairs. The nucleic acid bases are designated only near the restriction sites at the ends of the segment, but extend through and beyond the hypothetical segment shown. The representative restriction fragment would result from digestion of the genome with a restriction enzyme called *Eco*R1. *Eco*R1 recognizes and cuts only between the G and the A of the sequence GAATTC of the DNA strand. Because the sequence cut is palindromic, the bases in the free single-stranded ends complement one another, so the ends can pair by hydrogen bonding. Such single-stranded ends are called "sticky" ends. Sticky ends allow the DNA fragments to be reassembled with themselves or with DNA from other sources cut by the same restriction enzyme. After the fragments are assembled, a ligase is used to reform the covalent bonds cut by the restriction enzymes. The sticky ends can pair with the ends of other fragments or can wrap around and form a closed circle. The joints can be made covalent by a ligase. Bacterial plasmids are covalently closed circular DNA fragments that are able to replicate autonomously in the bacterial cell. When the plasmid is opened with *Eco*R1, the sticky ends bond with genome fragments forming closed plasmids, each containing a genome fragment. After treatment with a ligase, the modified plasmids can be transferred back into *E.coli* by transfection and grown in large amounts. Colonies of bacteria carrying the plasmid with the gene of interest can be isolated by various selective techniques.

B. Cloning

Cloning is the process of isolating and reproducing copies of the DNA carrying a gene's nucleic acid sequence. The gene must be cloned so that the transgene is a major component of the DNA injected into the zygote. Cloning is possible because of two kinds of enzymes that act on DNA, restriction enzymes and ligases. Restriction enzymes cut DNA strands at specific sequences. Many cut at palindromic sequences, producing uneven ends, as shown in Fig. 2 for a restriction enzyme called *Eco*RI. "Sticky ends" allow the DNA fragments to be reassembled with themselves or with DNA from other sources cut by the same restriction enzyme. After the fragments are assembled and held by base pairing, a ligase is used to reform the covalent bonds cut by the restriction enzymes. This combination of restriction enzymes and ligases makes it possible to disassemble a genome and reassemble selected DNA fragments as desired.

To clone a mammalian gene, the DNA representing the entire genome of the animal can be isolated from the other cellular constituents and cut into restriction fragments. (Fig. 2.) Many restriction fragments of varying lengths would be produced by the restriction enzyme. Ideally, each segment of the genome would be represented in the restriction fragment mixture. The fragment carrying the gene to be cloned can be replicated using a plasmid that grows in the common bacterium, *Escherichia coli* (*E.coli*). Plasmids are circular pieces of DNA which are able to replicate in *E.coli* independently of the chromosome. Each *E.coli* cell can have hundreds of copies of the plasmid per *E.coli* chromosome. The plasmid can easily be separated from the chromosome and can be cleaved with the restriction enzymes. The resulting sticky ends can form base pairs with the sticky ends of the animal genomic fragments produced by the same restriction enzyme (Fig. 2). After ligation, the result is a group of modified plasmids still able to replicate in *E.coli*, but each plasmid carries a different segment of the animal genome. The collection of plasmids can be introduced into and grown in *E.coli*, increasing the number of copies of each of the animal chromosomal fragments. The collection of plasmids is referred to as a gene library. Many bacterial colonies must be tested to retrieve from the library at least one colony carrying the plasmid with the gene to be cloned.

The frequency of plasmids in the library carrying the desired gene is low. If each plasmid carries a piece of DNA about the size of one gene, and there are 100,000 genes in the animal representing only 10% of the DNA (90% of mammalian DNA has no known function), one would have to test *at least* a million plasmids to find one carrying the gene being sought. This can be done by plating the bacteria carrying the plasmids onto petri plates so individual colonies can be examined. Each colony contains progeny from a single parental bacterium carrying identical plasmid, i.e., all of the plasmids in a single bacterial cell are identical, so each colony represents a single plasmid. Rapid techniques are available to screen colonies a plate-full at a time by looking for DNA that anneals to a radioactive or other suitably labeled probe carrying a DNA sequence complementary to the gene. The selection is usually designed so that the desired colonies are a different color or are otherwise clearly distinguishable from the overwhelming number of background colonies. When a colony carrying the gene is found, it can be grown in culture, the plasmid DNA isolated, and the gene removed from the plasmid with the restriction enzyme, and separated from the remaining plasmid DNA. The result is a relatively large quantity of the desired gene in pure form. This DNA can be used to produce a transgenic animal.

C. Introduction of the Transgene

At present, embryo injection (Fig. 1) is widely used for introducing DNA into fertilized ova, but other alternatives offer advantages. In chickens the fertilized ova are not readily available because the shelled embryo emerges at a much later stage of development. Retroviruses have been used to introduce DNA into chicken embryos because these viruses infect many of the embryonic cells and integrate into the host genome carrying the transgene. Like the plasmid discussed above, retroviruses can be modified to carry transgenes. Retroviruses integrate at nearly random single chromosomal sites and insert a single copy of the transgene. Retroviruses might be more widely used in agricultural animals, but the size of the DNA they can carry is relatively small and there are concerns about the possible reversion of the inactivated retrovirus producing infective virus particles which may infect other animals. Although such events are extremely rare, the use of retroviruses in food animals has not been widely pursued.

The introduction of recombinant DNA into ova as a hitchhiker stuck to the outside of spermatozoa has not been reproducible in mammals, but does show promise in fish. Fish sperm were incubated with transgene DNA and added to suspensions of eggs. The DNA was incorporated into the genome of about 30% of the treated eggs. The authors of this study confirmed integration into the genome by demonstrating transmission of the transgene from some of the fish through two generations. This technique is particularly easy in fish because the eggs are normally fertilized externally. The technique will also be useful in land animals if reproducible methodology can be found.

The introduction of transgenes through embryonic stem cells offers major advantages. Embryonic stem cells are undifferentiated cells removed from very young embryos at a stage called the blastocyst. Undifferentiated means the cells are able to give rise to a complete embryo, i.e., they are totipotent. The stem cells are treated with the transgene DNA and propagated in tissue culture. Single transgenic cells from the culture can be implanted back into young embryos by micromanipulation resulting in transgenic animals with mosaic patterns of cells because only the cells derived from the reimplanted cells carry the transgene. Studies show that the micromanipulation required to inject embryonic stem cells treated with DNA into a blastocyst can be eliminated by adding the treated stem cells to morula-stage embryonic cells in culture. The stem cells attach to the outside of the morula, but as development continues, they become part of the inner cell mass from which the embryo proper develops. This method simplifies the technique by eliminating the need to manipulate blastocyst-stage embryos, which are more difficult to handle. Both techniques produce mosaic animals, but germ line cells are frequently transgenic, so fully transgenic animals can be obtained from subsequent generations.

Other techniques applicable to cell cultures can be used with embryonic stem cells. The bulk techniques used to introduce DNA into cells in culture can be used to introduce DNA into stem cells. These include the use of a DNA calcium phosphate precipitate or DEAE-dextran for presenting the DNA to the cells for uptake or electroporation, the use of electric currents. Genes can also be introduced into cells ballistically. Small particles coated with DNA are propelled from special jets by air pressure or by electropropulsion and shot into cells. This technique has been widely used in plants, and the process has been patented for use in animals.

Cell selection can be used to target a transgene to any locus in the recipient genome, a process called *gene targeting*. Cells with the transgene integrated at a desired site on the chromosome can be selected by designing the vector with a "reporter gene," which is expressed only by cells in which the desired insertion event has occurred. Thus, it is possible to select cells with specific recipient genes that have been interrupted by transgene insertion. These specifically selected "knockouts" can be used to determine the function of a known genetic locus. Genes of the recipient can also be replaced by homologous transgenes carrying small changes to study the effect of minimal changes such as single base changes on gene function. Knockouts and replacements are contributing heavily to the understanding of developmental and physiological processes.

Embryonic stem cells provide an avenue for the introduction of yeast artificial chromosomes (YACs) into animal germ lines, permitting the introduction of very large pieces of transgene DNA. In the plasmid cloning described above, the size of the DNA insert has an upper limit of about 10,000 base pairs. YACs can carry pieces of DNA over a million base pairs in length. This is an important capability because some genes and their regulatory regions are very diffuse, and transferring the entire region may be important to achieve appropriate expression. YACs contain genetic elements that allow them to be replicated in yeast as another yeast chromosome, hence their name. YAC DNA can be separated from the rest of the yeast DNA and injected into zygotes as above, but the largest pieces of DNA are difficult to handle and are transferred by directly fusing yeast cells containing many copies of the YAC with embryonic stem cells. Very large pieces of DNA are incorporated into the embryonic stem cells and may be transferred to progeny when the stem cells give rise to the germ line cells.

Surprisingly, genes can be expressed after the direct hypodermic injection of DNA into somatic tissues. DNA coding for an enzyme was expressed in mouse muscle cells surrounding the injection site. Expression of the enzyme persisted for at least 30 days after injection. When the messenger RNA for the same enzyme was injected, enzyme activity peaked at 18 hr and fell to about 3% of the peak level by 60 hr. Although the RNA had a short half-life, the DNA persisted in the cell and was expressed, but was not integrated into the chromosome. DNA has also been inserted into somatic tissues by particle bombardment technology. In this experiment DNA was coated on the surface of tiny gold beads so that 10,000 copies of the gene were present on each particle. The particles were accelerated by electromotive force into liver, skin, and muscle, each of which showed significant expression of the gene.

Direct injection techniques hold great promise for vaccines. To vaccinate, the DNA coding for a viral protein can be injected into a muscle. The muscle cells take up the DNA and produce the viral protein which is recognized as foreign and stimulates an immune response. There are special advantages for vaccines against influenza, because the influenza surface proteins change rapidly as a result of mutations enabling viruses to escape the antibodies. The influenza virus nucleoproteins do not change, but the nucleoproteins are not exposed on the viral surface and are not accessible to antibodies. DNA injection results in the intracellular production of the nucleoprotein, and this stimulates a cellular immune response to the virus. The foreign intracellular proteins stimulate the response to infection by a subclass of white blood cells called the cytotoxic T cells. Since most influenza viruses have the same nucleoproteins, a nucleoprotein vaccine should protect against infection by a heterologous virus, i.e., a virus with a different surface protein. Although the mechanism is somewhat speculative, protection against a challenge by a heterologous influenza virus has been demonstrated in mice. Another advantage of DNA vaccines is their greater temperature stability. Whole cell vaccines and proteins are more temperature sensitive than DNA.

Intravenously injected DNA is also expressed in tissues. The DNA was presented in liposomes, artificial membrane vesicles, to promote the entry of DNA into cells. After intravenous injection into mice, the gene was expressed in many tissues, including heart, lung, liver, lymph nodes, and others. Expression continued for at least 9 weeks. DNA linked to molecules that bind specific cell receptors can be directed to specific tissues. These somatic cell techniques may be particularly useful as a different approach to growth promotion in animals. The introduction of a transgene during a late stage of growth rather than at the embryonic stage may be less likely to cause the kinds of health problems seen in the transgenic pigs (see below). This technology opens a new avenue to long-acting therapeutics.

D. The Control of Gene Expression

The introduction of a transgene is of no value unless the gene is expressed (except for knockouts). Once integration of the gene has been established, expression is determined by measuring the amount of specific messenger RNA or more directly by measuring the amount of gene product formed. Gene expression is regulated at the transcriptional, translational, and post-translational levels, but the discussion here is limited to regulation of the production of mRNA. The regulation of gene expression is biologically critical. All the tissues of the body, e.g., muscle, and liver, contain the same genetic information. Differences in the genes expressed in each tissue are what distinguish one tissue from another. The tissue distinctions are made during embryological development as the various tissues differentiate. Once differentiation has taken place, the pattern of expression usually remains constant, although levels of expressed genes change in response to physiological changes. For example, when glucose is present in the diet, insulin is released, and insulin turns off the production of a critical enzyme responsible for the formation of glucose from amino acids, phosphoenolpyruvate carboxykinase (PEPCK). Many enzyme levels change in response to metabolic shifts. In general, rapid changes are accomplished by activating preexisting enzymes by covalent changes or by structural changes induced by small molecules. The slower hour-to-hour changes are accomplished by changing the level of gene expression. Physiological balance or homeostasis is labyrinthine, and the regulation of gene expression is an important part of the homeostatic system.

The complexity of transcription control is illustrated by two types of regulatory regions, promoters and enhancers. Promoters are located just in front of the beginning of the coding sequence of the structural genes, and contain the binding site on the DNA for the RNA polymerase. Promoters are located just in front of the beginning of the coding sequence of the structural genes and contain the binding site on the DNA for the RNA polymerase. Promoters also have binding sites for *trans*-acting proteins produced elsewhere in the genome that are essential for the activation of transcription. *Trans*-acting proteins, also called transcription factors, frequently activate transcription only in the presence of hormones, growth factors, or other inducers. For example, the growth hormone promoter is activated by thyroxine. These kinds of interhormonal interactions are essential for maintaining the endocrinological balance. The metallothionein promoter is turned on only in the presence of zinc ion or other heavy metals and has been used to make transgenic animals with growth hormone levels that can be elevated by feeding zinc ion.

Enhancers also bind transcription factors, but may be located within the gene, or much farther from the gene than promoters either in front of or beyond the gene. Enhancers activate gene expression and are also responsible for tissue-specific expression. They have been used to direct the expression of genes producing therapeutic agents to the mammary glands in transgenic animals.

Two kinds of control regions possibly related to higher-order chromosome structure are important for transgene expression. Transgenic founder animals carrying identical transgenes vary widely in the levels of transgene expression. Transgenes integrate by nonhomologous recombination at random sites in the chromosome, frequently in tandem arrays (i.e., multiple repeats of the sequence). Differences in levels of expression do not correlate with the number of gene copies in the tandem arrays and have been ascribed to the position of integration in the genome. Locus control regions (LCRs) and matrix attachment regions (MARs) stimulate the transcription of transgenes, making transcription independent of the position of transgene insertion and proportional to the number of gene copies. The LCRs, which are specific to the family of β globin genes, contain multiple binding sites for general and specific transcription factors and improve tissue specificity. MARs, contain the sites at which the nuclear matrix or scaffold proteins bind to the chromosomes. Both MARs and LCRs may stabilize the open form of the chromosome making it available to *trans*-acting factors essential for efficient position-independent transcription. For example, when the whey acidic protein gene, a milk protein gene, was introduced into mice, the level of expression varied with the site of integration and did not behave as the endogenous gene through the lactation cycle and in response to hormones. When the same sequence was introduced adjacent to a MAR, expression became position independent of the site of integration and, in most lines, more closely paralleled the expression of the endogenous gene through the lactation cycle. Whatever the mechanisms, LCRs and MARs are likely to be useful for controlling gene expression in transgenic animals.

III. Agricultural Applications of Transgenesis

The agricultural applications of transgenesis in animals were stimulated by the appearance of the twice-normal-size transgenic mouse on the cover of *Nature* (*London*) in 1982 (Fig. 3). The picture excited the imagination of animal scientists, because it proved that a growth hormone gene from one species, a rat, could be transferred to another species, a mouse, and produce the expected phenotypic change in the animal. It seemed that growth hormone and other genes could be transferred to farm animals to improve productivity. Many growth hormone genes have been transferred into swine and sheep, but unfortunately the animals that expressed the genes displayed one or more sequelae which precluded their use as productive agricultural animals. They displayed pathological conditions which occur naturally, but were of greater frequency and intensity in the transgenic animals. The pathology included lameness, gastric ulcers, kidney disease, and infertility. The requirement for general good health in productive animals apparently limits the physiological phenotypic extremes attainable from either classical selective breeding or from transgenesis. The expression of a transgene must be tightly controlled to maintain the animal within a physiologically acceptable range.

Data from injected growth hormone indicate that in some animals milk production is increased, the meat is leaner, and the feed efficiency is enhanced. A well-regulated growth hormone transgene could be beneficial, but attempts to regulate the gene have not been successful. In some attempts the gene was linked to a metallothionein promoter, a promoter that turns expression of the gene on in response to elevated levels of zinc ion. Because the effects of growth hormone are less deleterious during the later stages of growth, the idea was to add zinc to the feed in a later stage of growth and reap the benefits without the undesirable effects. This worked well in mice, but pigs and sheep were less responsive to the metallothionein promoter. A few experiments have been done with other components of the growth hormone system, growth hormone-releasing factor (GRF) and insulin-like growth factor-1 (IGF-1). GRF is made in the hypothalamus and stimulates the release of growth hormone from the pituitary. The human GRF gene expressed in pigs did not stimulate growth hormone levels, probably because three amino acids were cleaved from the amino-terminal end of the GRF. In sheep, growth hormone levels were increased and resulted in the same effects as growth hormone transgenes. IGF-1 is produced in liver and other tissues in response to growth hormone and is responsible for many of the hormone's effects. Unfortunately, not enough data are available to make any conclusions about the effects of IGF-1 transgene in food animals.

Naturally occurring mutations cause "double-muscled" animals with, as the name implies, nearly twice the normal levels of muscle. These are somewhat like what the animals growth hormone might ideally produce, but because the increased muscling begins during embryonic development, the large fetus causes delivery problems. Unless the increased muscle development can be delayed until after birth, these natural mutations will have little commercial value.

Transgenesis in fish shows great promise. Growth hormone genes have been transferred into about 10

FIGURE 3 Shows two sibling male mice. The mouse on the left carries a rat growth hormone gene fused to a metallothionein control region. The mouse with the transgene weighs 44 g. The control sibling weights 29 g. [The photograph was taken by R. L. Brinster. Reproduced with permission from Palmiter, R. L. Brinster, R. E. Hammer, M. E. Trumbauer, M. G. Rosenfeld, N. G. Birnberg, and R. M. Evans. (1982). *Nature* **300,** 611–615.]

different species of fish. A salmon growth hormone gene linked to an antifreeze protein promoter produced transgenic fish that were six times larger than the control population at 26 months of age. Information is not yet available on the transmissibility of the gene or on the general and reproductive health of the fish. Nevertheless, the initial data are promising, and experiments with fish are far easier and less expensive than work with farm animals.

In farm animals, enhancers specifying gene expression in specific tissue have been useful. For example, pharmaceutical proteins such as clotting factors and tissue plasminogen activator can be produced at very high concentrations in milk. Directed expression can also be used to improve feed utilization. The expression of the gene for the enzyme cellulase was directed to the pancreas in mice. The result was mice secreting cellulase into the intestine along with the normal complement of digestive enzymes. Monogastric animals do not normally produce cellulase and are unable to digest cellulose in plant materials. With cellulase in the digestive juices, the mice will make more efficient use of plant feeds because they will be able to digest the cellulose component. The cellulase transgene might also improve the feed efficiency of swine. Ruminants are naturally able to digest cellulose because of microorganisms in the rumen that contain cellulase.

Targeting gene expression to specific tissues will also be used to change the composition of milk itself. Increasing the casein content of milk would improve its use for the production of cheese. According to a 1990 estimate, increasing the casein content by 20% could save the dairy industry 190 million dollars. Because human milk has long been the gold standard for infant formula, producers are attempting to make cow's milk more like human milk. Cow's milk contains very low concentrations of the protein lactoferrin compared to the amount present in human milk. By introducing a human lactoferrin gene into cows with its expression directed to the udder, the cow's milk will be more human like. Milk from such herds could be used to produce infant formula.

An Australian group is attempting to enhance wool production by increasing the level of the amino acid cysteine, which is limiting for wool production. They are introducing into sheep genes for bacterial enzymes for the biosynthesis of cysteine. In mammals cysteine is synthesized from the amino acid methionine which is required in the diet. Bacteria synthesize cysteine from serine, an endogenously synthesized readily available amino acid. By transferring the two necessary enzymes from bacteria into sheep, cysteine will be increased and may increase wool production.

Scientists are also examining a number ways to improve disease resistance in farm animals. One method is to insert transgenes coding for viral coat proteins into the germ line. Presumably these coat proteins occupy the viral receptors on the cell surface where the virus normally attaches to the cell preventing the attachment of real viruses. This has been somewhat successful in preventing some diseases in chickens.

Strategies for disease resistance have evolved with animals, as exemplified by interferons and the mouse Mx1 gene. In mice, the expression of a gene called Mx1 is induced by viral infection or by interferon. Expression of the gene produces resistance to infection by influenza virus. The mouse Mx1 gene linked to the influenza-sensitive promoter has been transferred into pigs. The pigs have not yet been challenged with virus to test immunity to influenza.

Because interferon prevents viral infections, scientists have considered inducing disease resistance by introducing an interferon gene that is constitutively expressed, (i.e., expressed in the absence of a specific inducer). Unfortunately, interferon is too toxic to be compatible with constitutive expression. However, in the mouse, human interferon is less toxic, and transgenic mice expressing a human interferon gene were resistant to infection by the pseudorabies virus. This suggests that the toxicity of β interferon can be controlled by amino acid sequence changes, and this would be agriculturally useful if human or interferons with other amino acid changes work in swine.

The use of transgenesis for herd improvements has not progressed as rapidly as one might have imagined in the mid 1980s. This is for a number of reasons, one of which is that selective breeding remains a powerful competitor. Even after a transgenic animal with useful characteristics is produced, it will still have to be bred to expand the line and to be certain the trait is stably expressed in its new background. Domestic animals are far more heterozygous than mouse lines, so animal-to-animal differences can be large. If a trait can be enhanced by selective breeding, transgenesis is not likely to be competitive. [*See* ANIMAL BREEDING AND GENETICS.]

The cost of producing transgenic animals is high. The cost of a single transgenic cow was estimated at one-half million dollars in 1991. The costs are associated with the husbanding of the animals, including the ova donors and animals synchronized in the estrus cycle as recipients for the injected zygotes. Because integration of the transgene is random in each zygote, many animals must be produced to find at least one expressing the gene at the right level. The costs for cows are especially high because they are uniparous. However, costs are less for sheep which frequently twin and still less for pigs which average about 10 offspring per litter.

Technological developments are rapidly overcoming some of these obstacles. Gene targeting and the use of MARs or LCRs are likely to reduce the variability with integration site. Bovine ova can be removed from cows at slaughter and matured *in vitro*, greatly reducing the number of animals that have to be kept on hand to maintain the supply of ova. The ability to produce somatic cell transgenics may turn out to be far easier than producing and selecting germ line transgenics. The introduction of DNA intravenously may be as convenient as using a long-acting drug, in this case with the period of activity measurable in days or weeks rather than hours.

IV. Food Safety of Transgenic Animals

The effect of transgenesis on food safety is an important consideration, because most agricultural animals contribute to the food supply. The benchmark for the evaluation of the food safety of transgenic animals is the food safety of traditionally bred animals. Selective breeding for desirable traits has been used for centuries and is not known to have produced unsafe lines of animals. This discussion of food safety focuses on those facets of transgenesis that distinguish it from traditional breeding. Three unique features of the technology are relevant, the transgene itself, the transgene product, and secondary effects arising as a result of the integration of the transgene into the genome of the animal. The transgene DNA sequence is not likely to be of concern unless it is infectious. The DNA of all the animals and plants we eat is ingested and digested with impunity. Even human DNA from the cells of the nasopharynx and the digestive tract is digested with the food. Hazards would only result from the DNA if the transgene were infectious and could replicate and infect cells in the gastrointestinal track or elsewhere in the body.

The transgene product can be thought of as a drug, and the food safety of the flesh evaluated as it would be for an animal treated with the drug. The primary questions would concern the toxicity of the protein and the concentration of the protein in edible tissues. As with drugs, secondary effects of the gene product must also be considered. Most proteins are not orally active, but some gene products increase the levels of other animal components such as steroids which are orally active. Because the function of the gene product is known before the gene is selected for transfer, the physiological systems affected are likely to be known, and the secondary effects can be evaluated. The transfer of a gene from a known allergenic organism into another organism is possible with recombinant technology because of the ability to transfer genes across species lines. Unless it can be shown that the gene transferred from a known allergenic source does not code for the allergen, consumers must be informed that the allergen may be present in an unsuspected food. The potential allergenicity of proteins new in the food supply might be predicted by structural similarities to known allergens, but the science is not developed well enough to be highly predictive.

The effects of the integration of the transgene are the most difficult feature of transgenesis to evaluate. Because transgenes integrate into the genome nearly randomly by nonhomologous recombination, they can integrate into the middle of a host gene stopping its expression (a knockout) or into a gene in a way that increases or decreases its level of expression by putting it under the control of the transgene promoter. Because these events are random, the consequences are not predictable. However, similar events do occur spontaneously from deletions, inversions, insertions, and point mutations during normal reproduction, and yet unsafe lines of animals from safe parental lines have not been described. Unlike plants, the common food animals do not produce substances that are toxic to humans in the food, but innocuous to the animal. Increases in orally active substances such as steroids are likely to be reflected in the health of the animal. Only changes in vitamin levels or other nutritional parameters are apt to go unnoticed if affected, but this is also true of traditionally bred animals. At the present stage of technological development, the safety considerations for transgenic animals are similar to those for traditionally bred animals or animals administered drugs.

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Transposable Elements in Plants

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Glossary

Autonomous element Transposable element with all the functions necessary to self-excise and reinsert at new sites (see Fig. 5A)

Autonomous mutability Mutability that is controlled at the locus, and does not need a second factor

Chromosome breakage Breakage induced by a transposable element; in the *Ac–Ds* system, it occurs at a special double *Ds* (see Fig. 2C)

Reporter allele Gene with a defective transposable element insert that responds to an active element (see Fig. 2A)

Tagging (gene) Using a cloned element probe to identify and isolate a gene with a transposable element insert for molecular studies

Target site duplication (TSD) Duplicate of a host sequence induced on insertion of a transposable element at a genome site (see Fig. 2A)

Terminal inverted repeats (TIR) Sequence at the terminal ends of the element that have a characteristic number of nucleotides that identifies a system (see Fig. 4)

Terminal motifs Series of characteristic sequences related to the TIR and extending on each end of transposable elements (see Fig. 5A)

Transposable element (TE)/transposon DNA segment containing functions that induce excision and transposition

Transposase Protein product of a transposon that induces excision

Transposition Movement of an element from one site on the chromosome to a new site

Variegation Chimeric sectors on plant parts

Transposable elements are DNA segments with a distinct structure and function(s) that allow them to transpose throughout the genome. Their phenotypic expression is derived from the insertion of these elements into genes whose functions are often interrupted, that is, a null phenotype. This can be followed by the excision of the transposon out of the gene, which allows the functioning of the gene and often leads to a wild-type phenotypic expression. This insertion followed by excision results in variegation. This variegation is a distinctive type representing a return of function of the gene and can be seen in all plant tissues where this gene is phenotypically observed to function. Forms of this variegation are illustrated in Fig. 1.

I. Phenotypes, Variegation, and Components

Originally identified in the 1800s as "eversporting" varieties and reported by early biologists, including Charles Darwin, H. Lecoq, and T. A. Knight, this type of variegation was finally elucidated when Barbara McClintock observed and then described a two-unit interaction that caused the breakage of chromosomes. From this original observation, the components of this two-unit interaction were then found to be the same components controlling the variegation of numerous genes. By relating the breakage phenomenon and the variegation phenotype, it was finally determined to be caused by these same units. In fol-

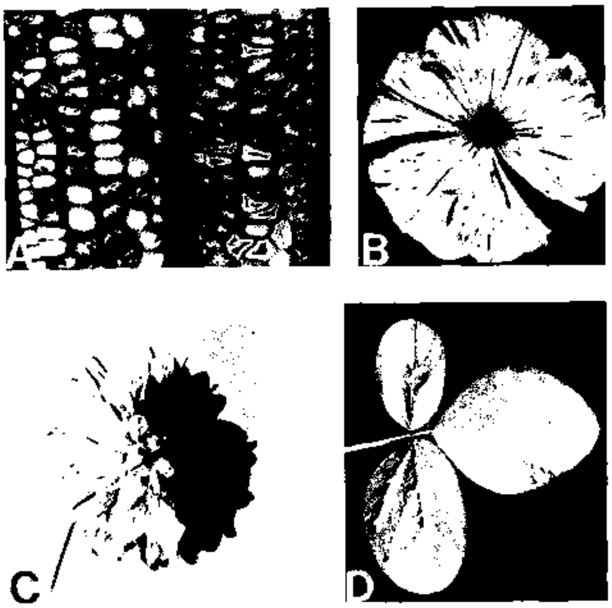


FIGURE 1 Varied variegation: (A) kernels of *Zea mays, a2m*; (B) *Petunia hybrida, an1* allele; (C) *Dahlia*, horticultural variety; (D) *Glycine max, Yn-18*. [From P. A. Peterson. (1987). Mobile elements in plants. *CRC Crit. Rev. Plant Sci.* **6**, 105–208.]

lowing the genetics of these units causing breakage, McClintock observed that they changed position. This was confirmed by the demonstration of the transposition of the breakage phenomenon, through genetic means, from one position of the chromosome to another, and finally the movement of these elements into numerous genes leading to variegation. It was therefore readily acceptable to conclude that the variegation of genes was related to the breakage phenomenon and that these units causing variegation were mobile. With these observations, transposable elements were introduced into the genetic literature in the early 1950s.

A. Origin

Most of the variegated genes found by McClintock arose out of strains of genetic material with chromosomes that included an inverse duplication of the short arm of chromosome 9 in maize and, with the resulting crossovers, that underwent cycles of chromosome bridges and breakage, followed by fusion of the broken ends. It is hypothesized that this breakage of the bridged chromosomes represented a stress condition affecting genome physiology that induced unknown effects that caused the mobility of these elements. Most likely, active transposable elements were already present in the genome but the stress conditions enhanced the mobility. This does not imply that the original transposable element arose under these conditions, in that the stress did not cause the origin of the elements themselves. Following the induction of the breakage of chromosomes, a condition was generated by the breakage activity that induced active elements already present in the genome to become mobile and by this mobility become inserted into genes, causing the variegation. In addition to this stress induced by the breakage phenomenon, variegated phenotypes appeared following irradiation such as in the Bikini atom bomb tests. Subsequent tests showed that these phenotypes were cases of mobile element inserts. Yet variegated phenotypes have been present in horticultural plants for centuries. Their pervasiveness in plant types was likely enhanced by horticulturists who selected them for their esthetic value as did native American Indians among their corn cultures. What conditions promoted their presence in these cultivars are unknown, but over a period of time, variable environmental changes could have been responsible. However, their initial origin and their entry into the genomes of plants is still a mystery. The homology of their structure and critical sequences across plant species and genera implies an ancient origin or a case of horizontal transfer. [*See* PLANT GENETIC ENHANCEMENT.]

B. Components

1. Autonomous Mutability

From early studies at the beginning of genetic investigations on transposable elements, two kinds of hereditary control of variegation were known that eventually led to the description of two kinds of elements. From genetic studies, it could be seen that when the transmission of a variegating gene was inherited as a unit (i.e., the gene in question when outcrossed was always inherited with the mutability), this indicated that the active component causing the variegation was located at the gene. This represented an "autonomous mutable locus." In current dialogue, this autonomous unit at the gene in question is the autonomous element. Carrying this further, it is apparent that the autonomous element has all the functions with the capacity to cause its own excision and reinsertion at a new site.

2. Two-Unit Mutability

The second type of variegation required two units. It could be determined genetically that the active element was inherited independently of the gene showing variegation. This variegating gene included a receptor element (receptive to transactive signals from the autonomous element, now identified as a defective element) that responded to the transactive functions of an active element located elsewhere. In later molecular studies, this receptor element was found to be similar to the active element but was deficient in a critical component of the active element (the autonomous element), lacking the necessary functions to self-excise, though it did include most of the structural integrity of the element that allowed it to respond to the active element by excising and transposing to another site.

Further study determined that these defective elements arose from deletions of important components of the active element. Their structures are identical except for variable missing parts that are necessary for inducing excisions and resulting in transposition. This will be described in the molecular description of elements. Thus the two kinds of variegation control, namely, autonomous vs two-component, represent the original element and a derivative defective type.

II. Genetic Determination and Resolution

A. Systems

With the establishment of these two-component systems, the defective form (the receptor) became available as a "reporter" allele. When a new unstable allele is discovered in a genetic study, it could be tested for its relationship to a previously described system in a genetic cross. This is illustrated in the following illustration whereby the reporter allele could be a *Ds* (dissociator of the *Ac–Ds* system) that responds by breaking the chromosome (phenotypically, the loss of genetic markers), and the new variegation (**Var**) could come from a native population. Other reporter alleles are indicated in Fig. 2A.

- The *Ac* element is the autonomous element.
- The *Ds* element is the nonautonomous element that responds to the autonomous element by excising, transposing, and inserting at a new site.
- Thus, *C Ds* is the reporter line for any *Ac*.
- A cross of *C Ds* × *c Ac* results in loss of *C* and is expressed as *C* to *c* variegation.

The cross must include a recessive *c* to expose the loss of *C* in the *C Ds* arrangement.

- **Var** is a new uncharacterized mutable phenotype.
- The unknown variegation (**Var**), if found in a commercial line, would be *c* **Var**.
- The question is whether **Var** is related to *Ac*.
- The *C Ds* line is crossed by *c* **Var**.
- If there is no variegation of *C* to *c*, **Var** is unrelated to *Ac*.
- If variegation results, **Var** is either related to *Ac* or **Var** is carrying *Ac* in the line, but is not the cause of **Var** variegation.
- A direct correlation of *Ac* effect and **Var** expression in successive crosses would prove the relation of **Var** to the *Ac* system, that is, **Var** expression is always correlated with *Ac* activity in an independent test.

Thus when a new form of variegation is uncovered, the variegation is crossed to the numerous and available transposable element system's reporter alleles (Fig. 2A). The particular selection of reporter allele depends on the genetic makeup of the line where the new variegation is found. These reporter alleles are listed in Fig. 2A. As a consequence, nine systems have been identified; however, there are, subcomponents of these systems that do not show reciprocity of activity to the response to this active transposable element. These are illustrated in Fig. 2B. Other elements have not been genetically defined. For example, the multitude and diversity of *cin* elements have not been followed genetically, and other undefined and uncharacterized inserts have been uncovered as genes have been isolated. Their identity as transposable element inserts is derived from a characteristic terminal inverted repeat (TIR) and target site duplication (TSD).

B. Specificity of Systems

As new variegation was found and tested against reporter alleles, a positive interaction indicated the same system [Fig. 2B(A)]. When a test was negative, mutable alleles fell into different families of elements, which indicated that there was a specificity of the autonomous element on the reporter allele. This specificity awaited molecular findings for an explanation. There was a genetic clue: the specificity of interaction with the specific autonomous element was related to the autonomous element that previously "visited" the locus. Prior to the molecular findings, a critical question was: How was the gene "contaminated" by the "visit." Transposable element families evolve such that reciprocity in interaction is absent [Fig. 2B(B)]. Further changes in a reporter allele occur when a "helper" element is needed with an active *En* element for transposition to occur ([Fig. 2B(C)]. In this latter

A **Transposable Element Systems**

	Non-autonomous (Reporter alleles)										
*Au**	*a-dt*	*Ds*	*I/dSpm*	*Ds1*	*r-R #2*	*r-cu*	*Mu1-Mu8*	*mut*	*mrh*	*rbg*	*rcy*
Dt	+										
Ac/Mp		+		+							
En/Spm			+								
Uq				+							
Fcu					+	+					
Spf					+						
Mu1R							+				+
Mut								+			
Mrh									+		
Bg										+	
Cy							+				+

+ = responds as mutability; absence of + indicates no response.

* = Au = Autonomous element

B Regulator-Receptor Interactions

		Receptor	
	Standard	1	2
A	Reg1	+	-
	Reg2	-	+
Uq case (Others)			
B	Reg1	+	+
	Reg2	-	+
Helper Case (*Med*)			
C	Reg1 alone	+	-
	Med alone	-	-
	Reg1 + *Med*	+	+

C

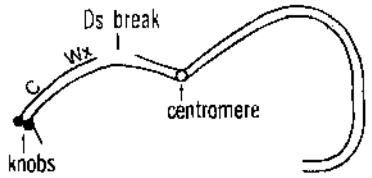


FIGURE 2 (A) Transposable element systems. Regulatory elements are specific in their activation (+) of receptor elements. There are three cases of overlap in activity: *Ac* activates all *Ds*'s, but *Uq* activates only *Ds1*; *Fcu* activates *rcu* and *R-r#2*, but *Spf* is limited to *R-r#2*; *Cy* and *Mu1R* appear to have homologous activity. (B) Types of exceptions to standardized transposable element systems. Case A: Reg 1 = *Ac*; Reg 2 = *En*. Rec 1 = *Ds* allele such as *wx-m7*; Rec 2 = an *I*-containing allele such as *a1-mrh*. Case B: Reg 1 = *Ac*; Reg 2 = *Uq*. Rec 1 = a standard *Ds* allele: Rec 2 = a *Ds1* allele (*wx-m1*). (Distinguishes *Ac* from *Uq*.) Case C: Reg 1 = *En*. Rec 1 = *wx-m8*; Rec 2 = *c2-m881058Y*. (Distinguishes the two different Receptors and uncovers Mediator.) The basis for the specificity of systems: + = mutability; − = no mutability; *Med* = Mediator. Case A represents two different unrelated systems. When one autonomous element transactivates a reporter allele, one would expect all autonomous elements acting on related reporter alleles to be a part of the same system. But as seen in Case B, there is no reciprocity. The same holds for Case C. This may relate to the evolution of transposable element systems. (C) The *Ds* on chromosome 9. [Modified from P. A. Peterson. (1993). Transposable elements in maize: Their role in creating plant genetic variability. *Adv. Agron.* **51, 79–124.**]

case, a chimeric reporter allele incorporated some genomic sequences from the host genome.

C. Transposition

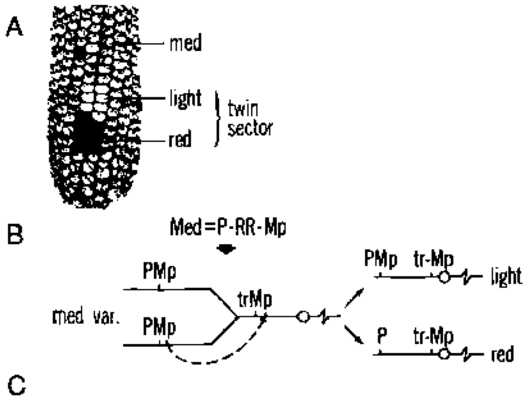
1. Genetics

The genetics of transposition was first revealed by McClintock in following the *Ds* unit that was in a specific position on chromosome 9 in maize. McClintock had originally identified this as the *Ds* locus, and specifically as a "weakened point" in the chromosome (i.e., this point in the chromosome readily dissociated). The breakage phenomenon observed in the original *Ds* position demanded that all the genes distal to the *waxy* gene (Fig. 2C) were lost owing to chromosome breakage. Subsequently, this breakage phenomenon included only the *C* locus, which was distal to *waxy*. Because the original breakage phenomenon position and the second position (near *C*) were dependent on the presence of *Ac*, it was concluded these were related events and that the *Ds* locus had moved from a position proximal (toward the centromere) to *waxy* to a position proximal to the *C* locus (Fig. 2C). In a further discovery, the C locus became mutable and because it responded to *Ac*, it could be concluded that this same unit (*Ds*) was involved in mutability. The origin of the variegated *c* allele indicated a further movement of the *Ds* element.

The movement of these *Ds*'s deemed to have come from transposition could also be explained by the origination of units already present at a chromosome site that respond to *Ac* without the necessity of invoking a transposition phenomenon. This was finally settled by the study of variegated pericarp in the origin of twin sectors (Fig. 3A), which represented unambiguous evidence for transposition.

2. Mechanism

Plant transposable elements transpose via a conservative mechanism whereby the movement of the element by excision from a donor site is followed by reinsertion at a recipient site via a so-called "cut-and-paste" method. Variegated pericarp and the associated origin of twin sectors represented unambiguous evidence for transposition (Fig. 3A). The pericarp locus (*P*) conditions a dominant red coloration of the pericarp that envelopes the kernel and, thus, the aleurone. Unstable pericarp represents the change of a colorless form of pericarp to a colored form and the resulting variegation is featured as longitudinal stripes from the base of the kernel to the crown involving numerous sectors. (Fig. 3A). R. A. Brink and his students, following R. A. Emerson's early work on variegated pericarp, were able to demonstrate that one pattern of pericarp variegation, namely, a medium type, often changed to a light type and this change was proven to be caused by the inclusion of a transposed element (*trMp*) that reduced the variegation of the original mutable pericarp to a light type of variegation. The element at the *P* locus was designated *Mp* for modulator of pericarp and the final designation was *P-Mp(P-RR-Mp)* (variegated cob and pericarp) for the *P-vv* allele (Fig. 3C). The excision of *Mp* from *P-Mp* results in a red coloration of the maize cob and pericarp. This appeared as large sectors on the ear because this was pericarp variegation. Also appearing on the ear and covering several kernels were light variegated sectors that in a later analysis were shown to be the original *P-Mp* plus a transposed *Mp (trMp)* in the same clonal sector. The genetic studies readily showed that *trMp* was inherited in a linked or independent position from the *P* locus. This *Mp* was eventually shown to be homologous in structure and function to *Ac* (Fig. 2A).



C

Allelic designations	Abbreviated terms	Phenotypes
P-RR/P-WR	RR/WR	Red
P-RR-Mp/P-WR	VV/WR	Medium-variegated
P-RR-Mp/P-WR + tr-Mp	VV/Wr + tr-Mp	Light-variegated

FIGURE 3 (A) Mutable pericarp with medium, light, and red phenotypes. (B) Mechanism of transposition via replicating chromosome. (C) Allelic designation of mutable pericarp. [Modified from P. A. Peterson. (1987). Mobile elements in plants. *CRC Crit. Rev. Plant Sci.* **6**, 105–208.]

The question remained regarding the origin and resulting insertion of the transposed *Mp*. The fortunate observation of twinsectors of red coloration that was twinned with a light variegated coloration (Fig. 3A) was the clue needed to unravel the basis of the origin and reinsertion of the transposed *Mp*. It became apparent that the *P* allele arising from *P-vv* resulted in a red sector. Coincident with that was a twin light variegated sector. A single event was the basis of the twins, the origin of the *P* allele red sector, coincident with the origin of the light variegated sector (Fig. 3A). The subsequent finding that *trMp* was located at the identical chromosome sites in both sectors—the gametes arising from the red sector and those arising from the light sector—confirmed the single-event hypothesis. The excision of one *Mp* from one *P-vv* allele was now located at two sites, one that included the *P*-containing chromosome yielding a red sector and the other on the sister *P-vv*-containing chromosome yielding a light phenotype. This transposition event was shown to arise by excision from a replicated strand to an unreplicated strand during chromosome replication. This is illustrated in Fig. 3B, showing *trMp* replicating at the new site. It could readily be concluded that the change in variegation pattern (medium to red and to light) was associated with the transposition of an element. This is an unambiguous demonstration of transposition, namely, a "loss and gain" observation. The allelic designations associated with these phenotypes are shown in Fig. 3C.

3. Localized Transposition Site

Transposing elements have a high affinity to reinsert at nearby chromosome sites. This is amply demonstrated with the *Ac/Mp* element and with the *En* element. The explanation for this has not been clarified, but the mechanism, as illustrated in Section II,C,2, suggests that there is an affinity for replicated strands and an excision from an unreplicated strand. This was questioned by later studies with the *En* element where the most apparent type of transposition is from a replicated strand to another replicated strand. This differs from the case with the *P* element. However, the twin spots were a phenotypic assay for transposition and this demanded that the element must transpose from an unreplicated strand to one that is replicated in order to provide the expression for the twin sectors. An explanation for this transposition to nearby sites was provided by the *Antirrhinum* studies of Coen and his group, whereby a model was suggested that the normal transposition involves a physical association between the donor and the recipient sites. This also implies that a transposed element is not floating free of any attachment in moving from a donor to a recipient site. According to the Coen model, there is a preferential insertion to recipient sites that are spatially in proximity to the donor site that shows some homology (e.g., a small duplication) to allow an exchange. And if a chromosome condition (i.e., a replication mode) was also necessary, the same chromosome would offer a more receptive site for insertion. The inability to find a free-floating element in molecular studies supports this model's assumptions as well as the numerous studies that have demonstrated transposition to nearby sites.

III. Molecular Description

A. Structure

Following the genetic discoveries of systems and the mechanism of transposition, as well as the specificity of systems, the elucidation of the *Ac* transposable element and its derivatives dissipated the mysteries regarding these genetic features. This came initially from studies of the autonomously mutable *wx-m9* and its derivative. The initial studies with the *wx-m9* allele made it possible to compare the active element at the *wx-m9* locus with the *wx-m9* receptor allele, which was a derivative nonfunctioning element. By making a comparison of the DNA sequence and structure of the two alleles, it was possible to clarify how an autonomous element could give rise to a two-element system. This also illustrated how the *waxy* allele first "visited" by the autonomous element left behind a "signal" that allowed it to respond only to that particular element. It was found that the autonomous *Ac* element was approximately 4500 nucleotides long (Fig. 4).

When the *wx-844* allele was isolated in an isolation plot, it was then possible to describe the *En/Spm* element. This element is 8.3 kb in length and also contains a definitive structure. By examining the full-size sequence of the element and comparing it to the recovered cDNA, it was shown that there were 11 exons and 2 open-reading frames (Fig. 5A). In addition, the definitive TIRs on the ends of the element and the identifying sequences in the host chromosome, the TSD, were characterized. As opposed to the case with *Ac*, where the TIRs were 11 in *Ac*, there were 13 in *En/Spm* and the TSD was 8 in *Ac* and 3 in *En/Spm* (Fig. 4).

The structure of the transposable element had a further identifiable structure (Fig. 5B). With the *En/Spm*, in addition to the characterized TSD and TIR, there were a series of common motifs (12 and 13 bp) in the terminal 200 base pairs of the element. The later studies showed that these common motifs were

Element		Plant	(kb)	Terminal inverted repeat (bp)	Duplication of target site
Ds1	nAu	*Zea mays* L.	0.405	11	8
Ac1	Au	*Zea mays* L.	4.563	11	8
En1	Au	*Zea mays* L.	8.287	13	3
Spm-18	nAu	*Zea mays* L.	2.241	13	3
Mu1-Mu8	nAu	*Zea mays* L.		+200	9
Bg	Au	*Zea mays* L.	4.869	5	8
rbg	nAu	*Zea mays* L.		5	8
rcy:Mu7	nAu	*Zea mays* L.	2.2	+200	9
Mu R1		*Zea mays* L.	4.0	+220	9
Tam1	Au	*Antirrhinum*	17.	13	3
Tam2	nAu	*Antirrhinum*	varies	13	3

FIGURE 4 Molecular characteristics of some examples of transposable elements. Au, autonomous; nAu, nonautonomous.

in a defined orientation (head to head or tail to tail) and this was very important in maximizing excision efficiency.

Previous genetic studies showed that there were two functions of *En/Spm* with identifiable phenotypic effects. These included a *Mutator* function and a *Suppressor* function. Very early in the description of the element, two transcripts could be identified in Northern blots—a heavy-staining 2.5-kb band and a light-staining 6.0-kb band. With the aid of certain mutants that had an impaired *M* function, it could be determined that the 11 exons were associated with the *S* function. With the various mutants it was possible to show that the *Suppressor* function was allied to the 11 exons. The *Mutator* function was assigned to the two open-reading frames. A further definition of the open-reading frames showed that the ORF1 was most important in the full capacity of the *Mutator* function. The middle segment of ORF1 was also allied with considerable homology to the *Mutator* function of the *Antirrhinum* transposon.

Because of the uncertainty of how the residual *En*'s were contributing to some of the functions leading to the phenotypes, investigators found it important to make transgenic plants with tobacco with each of the components of the transposon. This included

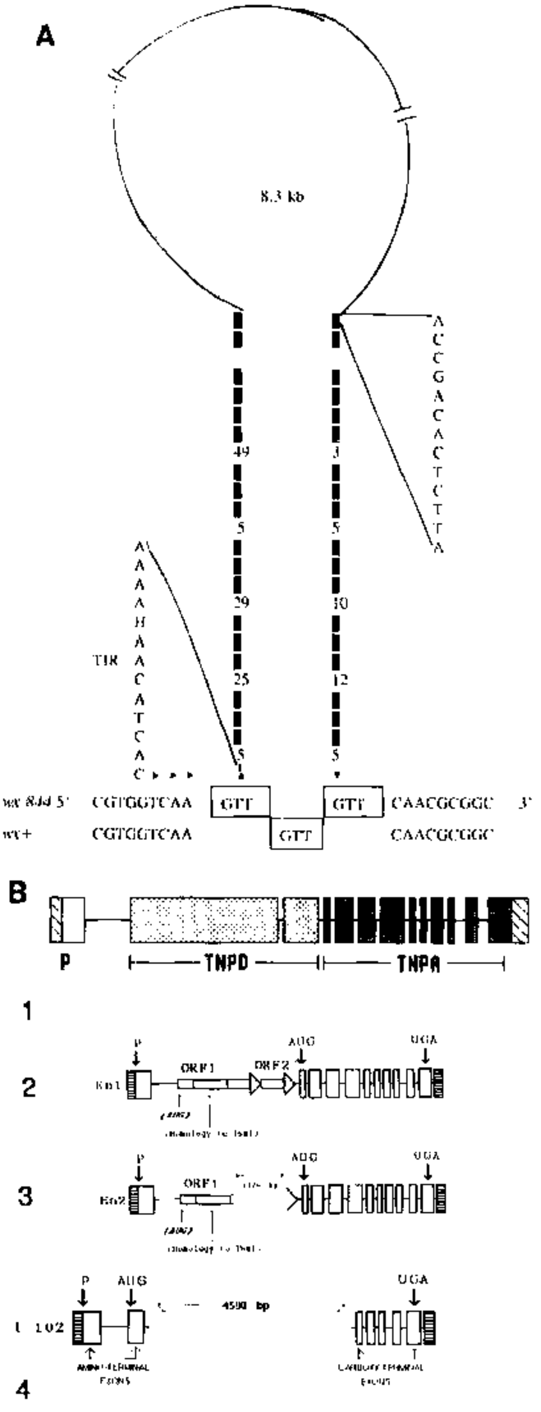


FIGURE 5 (A) Molecular description of the *En/Spm* transposable element in maize. This 8237-bp element is characterized by a host target site duplication (GTT) and a 13-bp terminal inverted repeat. The long terminal (200+ bp) that incudes common motifs is variable in length on each end (the dark dashes) and these are interrupted by variable segments that represent gaps between the common motifs. (B) Part (1): TNPA, TNPD *En/Spm* structure. Part (2): The *En/Spm* ORFs and exon distribution. Part (3): *En2* has a deletion of ORF2 and part of ORF1. Part (4): The *I-102[a1-m(r)]* allele has a gross deletion of 4590 bp. [Modified from P. A. Peterson. (1993). Transposable elements in maize: Their role in creating plant genetic variability. *Adv. Agron.* **51,** 79–124.]

transgenics with the 11-exon unit (the *Suppressor* component TNPA in Fig. 5A) and transgenics with the two open-reading frames (the *Mutator* component TNPD in Fig. 5A). When each of the transgenics was individually grown, no excisions occurred. When the transgenics were combined in a cross, they showed transposition. This confirmed the genetic studies illustrating the *Mutator* expression functioning only with the *Suppressor* activity. The use of mutants and derivatives made it possible to identify the two transcripts to *En* structure. From these sequences the two proteins, TNPA and TNPD, could be identified (Fig. 5B).

A model was presented based on these studies showing that the most effective excision was made possible by the correct orientation of the terminal 200-bp motifs (Fig. 5A). The model showed that the *Suppressor* protein (TNPA) enveloped the terminal 200 bases and was attached to them like a zipper and that the *Mutator* function (TNPD) was then able to cut out the element following this very rigid alignment. Of course, the TIRs without the transposase are not in proximity to each other and the *Sp* protein must bring them together to begin the proper alignment. This was necessary to have the full TIRs cut in a manner so that they would be transposed intact to the site.

1. Footprints

First, the second TSD (Fig. 5A) represents additional nucleotides in the genome, which becomes a resource for changes in genome sequences. In most studies of transposable elements in plants, the excision process from the host TSD is rarely perfect, which results in recognizable footprints that are a clue that a transposon has been excised from the site. These footprints are recognized from the duplications that occur in the insertion of the element at a given site, which is illustrated with an example from the *En/Spm* element with the TGA TGA sequence or in the *Ac* system with a CATGATGC CATGATGC sequence. This duplication occurs with the insertion of the element and becomes a resource for alteration following the excision of the element. This alteration occurs during the excision process whereby free DNA strands are subject to endonuclease degradation and some new nucleotide sequences are generated. The latter was first demonstrated with the *Adh1* locus in maize and a number of revertant types that identified alterations following an excision. These alterations result in changed sequences that lead to altered proteins, some of which can be recognized phenotypically. Some include frameshift changes and the addition of nucleotides, which of course result in new phenotypes, and others include changes that result in additional amino acids, leading to altered proteins and some with a deficiency of other amino acids. With this correlation between change of nucleotide sequence and protein performance, it is surprising that often no phenotypic alteration is observed. In other cases, the alterations are phenotypically evident. The *Mu1* element generates gross deletions upon excision. It is likely that the absence of phenotypic alteration in some excisions may indicate that the change has little effect on protein performance because of the protein domain that is affected. These footprint changes have also been important in indicating the different components of the protein.

IV. Methylation Effects

It is often observed that the elements become quiescent (inactive). Furthermore, a number of inactive elements that reside in the genome become activated. This quiescence has been ascribed to methylation. Genetic inactivation of the *En/Spm* element is correlated with the sequences surrounding the element's transcription initiation site. Not only does methylation occur, but it occurs at different times in the reproductive cycle of the plant, and it increases during vegetative growth development of the male and female inflorescences and thus is transmissible. It was further shown that the susceptibility of the element to be methylated and to subsequently change during development correlates with the element's phase of activity. Thus, genetic stability associated with the spread of the methylation of the element's transcription initiation site leads to an inactive phase for the element. It was concluded that the methylation of residues within specific regions of the element is significant in maintaining the inactive phase of the element and thus leads to the regulation of the expression of the element during plant development.

The heritability of these methylation problems in several studies strengthens the universality of this in causing the quiescence of elements. Furthermore, the element maintains its inactive phase over several generations of selection. Thus this epigenetic mechanism is significant in dampening the effect of the element in populations. It appears that the unstable form of the element is programmable, which is heritable during the developmental cycle. An inactive element does change to an active one and this was found to be promoted by exposure to an active one. Or in some cases, gametes originating from tillers of plants lead to a heritable reactivation of the element. Further studies showed that the correlation of the element's genetic activity and its transcription activity was related to the methylation of C residues at the transcription site of the element.

When a reporter is introduced into a commercial corn variety or inbred, sectors of mutability are often observed and, if pursued, active elements are identified. Though these elements have not been verified as arising from methylation-suppressed elements, it can be assumed that their quiescence was so related. Even though such studies have not been pursued with many reporter alleles, it is very likely that the maize genome does carry such suppressed elements. On the other hand, when successive generations of corn populations are followed in a search of active mobile elements, elements that are active e.g., *Mrh;* see Fig. 2A) in early generations become extinguished in activity in later generations, further supporting the dampening effect on elements imposed by the genome.

V. Effects on Gene Expression

A. Phenotypic Changes

From early genetic studies, a number of derivatives of transposon-containing genes showed altered phenotypes, which indicated that the transposon induced heritable changes at the gene. This was explained in later studies by the residual "footprints" that leave the TSD duplications changed, yielding an altered reading frame leading to an altered protein.

One of the first studies that uncovered altered phenotypes was the *Dt* affect on the *A* locus that included an *a1-dt* allele. A number of revertants were uncovered and they could be distinguished. Though the majority were of the standard type that included the confirmed red color pericarp and thereby identical to the original *A1* allele, two exceptions to the majority showed different pericarp coloration. Furthermore, there was a different level of dominance. This was the first case of heritable alterations induced by a transposon effect on a locus.

Of course there is a bias in the lack of definition of the other 27 reversions that did not show any alteration. Probably, given more extensive and sensitive enzyme tests than are now possible, further alterations in the protein could be established. With the computerized simulated studies with proteins with altered amino acid distribution and content, different charges and domain effects could readily be identified.

B. Enzyme Changes

The footprints from the *Adh-1* locus harboring a transposon showed differences. There were reduced levels of mRNA in Northern blots of the *Ds*-induced change of the *Adh-1F* and *Fn335* alleles. It is likely that the position of the insert was important in affecting this phenotype in view of the positioning of it at the start of transcription and the processing of the dehydrogenase message. Altered thermostability of other alleles also could be shown. These same kinds of events affected the *wx-m8* allele. The derivatives would show altered amino acid content, which would yield altered proteins. Probably the most significant changes were found with the enzyme color series in maize. This is also true with the transposon-induced derivatives of the *Antirrhinum* series as well as the *petunia* mutability.

In one study in maize it was found that the *C1-S* allele differs from the standard *C1* allele or *C1* allele by a change in box 2 of the promoter. There is a possibility that this alteration was caused by a transposon as there is a typical 5-bp transposon-induced footprint in the vicinity of this 3-bp change in box 2. The latter results in an overexpression of the *C1* allele.

Other studies, such as a change in the promoter of the *Niv-53::Tam-1* mutant, also gave alterations. In four derived mutant lines, the *Tam-1* element was deleted, leaving altered flanking sequences of the chalcone synthase promoter. In one case, the TATA box of the chalcone gene was removed and this resulted in an extremely low expression of the gene, which mandated a new initiation site for gene transcription. Other mutants were overexpressed and others showed lower levels of expression.

Combining the presence of footprints and the phenotypic changes, it is quite evident that transposons are significant in altering protein structure and function. This is clearly evident whether it affects promoters or the structural component of the gene.

VI. Pervasiveness in Populations

A. Determination

With the available reporter alleles, it was possible to canvas populations for the presence of active transposable elements. This was first examined in the Iowa

Stiff-Stalk Synthetic (BSSS) maize population. It was surprising to find that the *Uq* element was most significant throughout all the improved BSSS populations. It was further found that there was a founder line that harbored an active *Uq* element that pervaded the whole population in subsequent selection programs. Later studies showed that the different programs were significant in the spread of the element throughout the population. In some lines, it became a major component of a population, whereas in other lines it was practically eliminated. The *Mrh* element was also found in high frequency throughout the populations.

It was also questioned how only the *Uq* element, which is homologous to *Ac*, could become pervasive. The *Uq* element may be a dampened-down element as it is limited in its activity, whereas *Ac* would be too excessive in its gross effects on genes.

Other elements are present in the maize genome, and certainly the *cin* and *tourist* elements are present in very high frequency in an extremely heterogeneous form. What effect this has on the genome is not known because only a few genes have been uncovered that harbor these elements, though *cin* has been identified in the corn progenitor teosinte.

B. Origin from Quiescent States

If a reporter allele is available in a series of lines, a frequent observation is that of small spots or sectors of spots. This would indicate that the reporter allele is responding to an active element and that the active element is changing from a quiescent to an active state. This was first seen with the *Uq* element in a survey of maize populations. A further search uncovered germinals of the *Uq* element and these were found to be diverse. This observation, coupled with the methylation of elements mentioned earlier, indicates that there are active elements in the methylated state and the demethylation is commonly occurring. Although there has not been a grand survey of these elements with reporter alleles in these populations, this has now been found with the *Uq* and the *Mrh* elements, which would indicate that the elements are maintained in a quiescent state under these methylation conditions and then they become fully active. And, if a condition becomes significant in changing the physiology of the genome, this would enhance the activation of these elements.

Transposable elements are also found in the maize progenitor teosinte. These elements in teosinte have characteristics of transposable elements and have not been studied in terms of their activity, but they do have the characteristics of transposable elements with reference to TIRs and TSDs.

VII. Plant Types Other Than Maize

Though the most intensive molecular studies have been with the two elements in maize, namely, *Ac* and *En/Spm*, the *Mu* element has also been analyzed. In other plants, such as soybeans and *Antirrhinum*, there have also been extensive molecular studies. What is generally true is that the elements in these other plants have the same general structure and, in the case of *Antirrhinum*, a homologous transposase sequence as in maize.

The *Antirrhinum* studies have been very significant in providing resource tools to analyze gene structure and function. The numerous derivative types arising from the transposon effect at a locus have given researchers adequate alleles to follow flower organ development and the interaction of the gene domains leading to flower development. Other studies with the *Tam-1* of *Antirrhinum* have elucidated the paramutability phenomenon. When Stable White *niv-44* is crossed with *Tam-1*, a large proportion of the F_1 progeny are *pale* on these and are *pale* in subsequent selfings. The heritable expression of mutability is similar to that in the maize paramutability studies.

Not many other mutability patterns of plant types have been followed except for the mutable alleles from *Petunia hybrida* and *Antirrhinum majus*. The *petunia* unstables follow the maize unstables in showing both autonomous and two-element interactions for control of mutability. Transposition patterns have been followed in the genetics of *petunia*. The *petunia* studies, as well as *Antirrhinum* studies, further strengthen the universality of transposons in a wide assortment of plants and also demonstrate that there is a universality in the structural components of the transposons. Similarly, the transposons found in soybeans and the candystripe locus in sorghum further support the prevalence of transposons among many plants.

VIII. Exploiting Transposons

A. Tagging

In addition to the evolutionary role of transposons in generating variability and their possible role in commercial line development, the other area of intensive study has been the use of transposons in tagging genes, which is the source of most of the genes that have been studied in maize. This has been most useful with the *Mu*, *Ac*, and *En/Spm* elements. Many researchers have exploited the *Mu* element in both general studies and the tagging process. Without the use of transposons in tagging, the studies with maize genes would have been seriously hampered. From this process, gene structure has been elucidated as well as the network of interactions, for example, as in the anthocyanin pathway, in demonstrating the kinds of interaction that take place in many of these plants. This tagging process was first exploited in *Drosophila* with the *P* elements, but it was intensively used in the maize plants. Their ready availability in maize lines has made their use very common. Further, these transposons have been put into transgenic plants and have been used in tagging in *Arabidopsis*, tobacco, tomato, and other plants. This process has probably been the most utilitarian aspect of transposons.

B. Protein Structure

Protein structure has been previously alluded to. In the study of the transposon-induced *C1* mutants in maize, two features of the acidic domain, helicity and charge, were investigated. Some mutants (*pale*-colored aleurone) caused the interruption of the helix and the introduction of one positive charge, whereas in another mutant the charge is reduced by a factor of seven though the phenotype is maintained (*pale*). It could be concluded that the ability to form an alpha helix in the *C1* protein is more important than the charge distribution within the domain. Thus the expression of the proteins could be visualized by changes induced by transposons in causing footprint changes, which are effective in causing the final phenotype change. Work will continue to progress in this area because of the numerous sites where the transposon insert can be found in a gene. With the current simulation studies of amino acid changes related to protein configuration, this will be a more generally used process in protein studies.

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Tropical and Subtropical Fruit

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Glossary

Mediterranean Areas with cool wet winters and hot dry summers; days in summer are above 30°C for several weeks and water use exceeding 250 mm month^{-1}

Subtropical Areas with winter minima of 5°–10°C and summer maximums of 30°–35°C; frosts may limit tropical fruit production even at low elevation and rainfall is generally greatest in summer and least in winter or spring

Tropical Lowland areas with mean temperatures above 25°C for most of the year or 8°–10°C cooler at higher elevations up to 2500 m; frost may limit tropical fruit production above 1600 m and rainfall may be continuous or there may be one or two distinct wet seasons

Tropical and subtropical fruit play a major role in the diet of many people and can be found as part of subsistence agriculture, as part of market gardens, and more recently in extensive private and corporate plantations. Fruit were traditionally sold in local markets and eaten fresh or cooked. However, in recent years many of these industries have developed large processing and export components which generate significant income.

I. Tropical and Subtropical Fruit Production

The major tropical and subtropical fruit are citrus (73 Mt), banana (71 Mt), mango (15.7 Mt), pineapple (9.7 Mt), papaya (4.4 Mt), and avocado (1.5 Mt). Citrus include a diverse range of fruit with orange accounting for about 70% of the production. Other major species are mandarin (12%), lemon and lime (9%), and grapefruit and pummelo (6%). There are no separate statistics for the last two mentioned groups, but it is estimated that 90% of the total production comes from lemons, while grapefruit also dominates over pummelo. [*See* CITRUS FRUITS.]

Tropical and subtropical fruit are grown over a wide range of environments from about 45° N to 35° S latitude. The climates are generally warm moist tropical, subtropical, or Mediterranean (Fig. 1). In true tropical lowland areas, mean temperatures are above 25°C for most of the year. Some fruit species can also be grown at higher elevation in the tropics up to 2500 m where mean temperatures are about 8°–10°C lower. There may be continuous rainfall or one or two distinct wet seasons. Subtropical areas generally have winter minimums of 5°–10°C and maximums in summer of 30°–35°C, depending on elevation and distance from coastal influences. The occurrence and frequency of frosts may limit tropical fruit production in these locations. Rainfall is generally greatest in summer and least in winter or spring. Mediterranean climates have cool wet winters and hot dry summers with day temperatures in summer of more than 30°C for several weeks and water use exceeding 250 mm month^{-1}.

Tropical fruit can be separated into different groups according to their pattern of growth and flowering. Citrus, mango, and avocado are multiple-branching trees with cyclic shoot growth, axillary (citrus) or

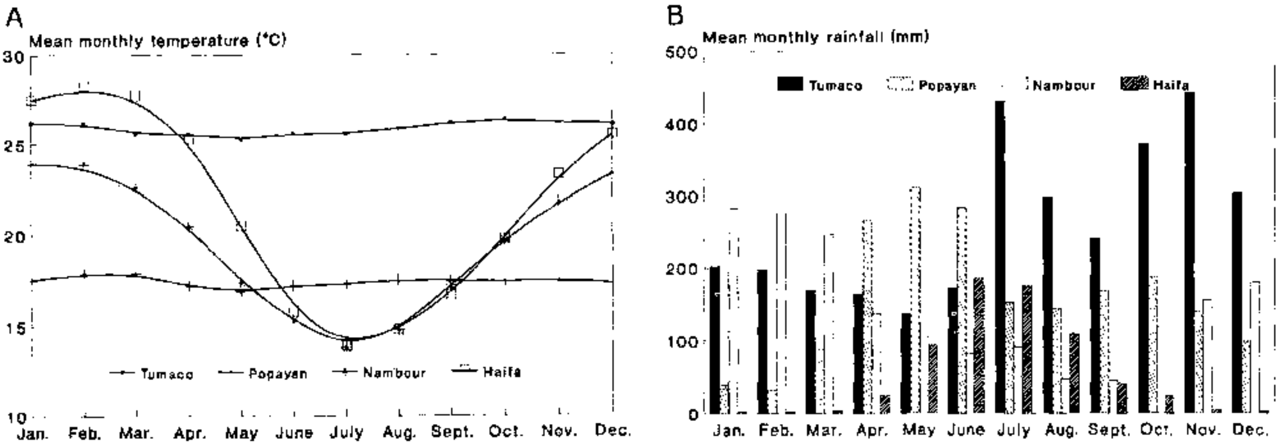

FIGURE 1 Average (a) mean monthly temperature and (b) rainfall in different tropical and subtropical fruit growing areas: Tumaco, Colombia (Lat. 2° N and 4 m elev.); Popayan, Colombia (Lat. 2° N and 1789 m elev.); Nambour, Australia (Lat. 27° S and 29 m elev.); and Haifa, Israel (Lat. 33° N and 10 m elev.). Months are southern hemisphere equivalents.

terminal flowering, and low average yields of <25–30 t ha^{-1}. Vegetative growth often competes with reproductive growth and a low proportion of dry matter is diverted to the fruit. Best yields occur when growth is limited to certain times of the year. Flowering generally occurs after a period of temperatures below 25°C and/or moisture stress. In contrast, the other major fruit species are single-stemmed with continuous leaf initiation at least until flower induction which is either terminal (banana and pineapple) or axillary (papaya). Yields are high and usually greater than 40–140 t ha^{-1}. Since there is no competition between reproductive and vegetative growth, yield is often proportional to the amount of leaf area. A high proportion of dry matter is allocated to the fruit and best yields occur when vegetative growth is encouraged. Flowering is generally not induced by cool or dry weather.

II. Citrus

A. Origin, Distribution, and Commercial Importance

Citrus includes many species and hybrids from the family Rutaceae. Most species originated in Southeast Asia and the Pacific, particularly from China and India to New Caledonia. The only exception is the grapefruit from the West Indies. The most important species are

Citrus sinensis—sweet orange
Citrus aurantium—sour orange
Citrus reticulata—mandarin
Citrus limon—lemon
Citrus aurantifolia—lime
Citrus x paradisi—grapefruit
Citrus maxima—pummelo

In official estimates, oranges are the most important citrus followed by mandarin, lemons and limes, and lastly grapefruit and pummelo. Citrus have a long history in Southeast Asia with unofficial records indicating cultivation in China for possibly 4000 years. They are now widely grown throughout the tropics and subtropics approximately between 44° N and 35° S with production of more than 1.0 Mt in the United States, Mexico, Brazil, Argentina, China, Japan, India, Iran, Pakistan, Egypt, Turkey, Greece, Morocco, Italy, and Spain. Citrus is the most widely grown tropical fruit and significant volumes of fresh and processed products are traded.

B. Botanical Relations and Cultivars

The taxonomy of citrus is complex with many species, hybrids, and cultivars. Many of the species are polyembryonic.

C. Description of Plant (Fig. 2)

Citrus are usually small trees armed with single axillary spines. Leaves are generally thin, dark glossy green with a strong aroma when crushed. Flowers are generally borne singularly and are mostly bisexual. Fruit are berries with green, yellow, or orange skin, thick leathery rind, and a yellow, orange, or red inner layer consisting of several segments filled

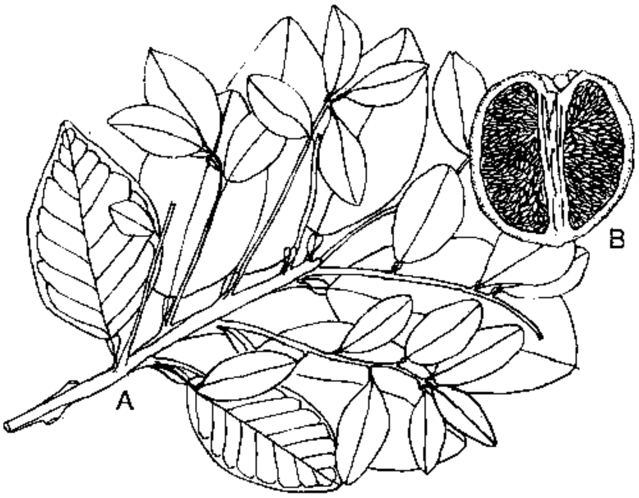

FIGURE 2 *Citrus sinensis* (sweet orange cultivar Washington Navel). (A) Vegetative shoot (× 1/2). (B) Fruit in longitudinal section (× 1/2). [Redrawn by Cathie Menzel with permission from Purseglove, J. W. (1968). "Tropical Crops—Dicotleydons," Fig. 83, p. 515. Copyright © 1968 by Longman Group U.K., Harlow, U.K.]

with pulp vessels. These vessels are firm or soft, filled with sweet, acid, or very acid juice with or without distinct oil droplets. Fruit usually have many small to large seeds, although some cultivars are seedless.

D. Growth and Development

Most *Citrus* are polyembryonic with seedlings true to type since the zygotic embryo is usually suppressed. There are some exceptions including the pummelo (*C. maxima*) which are monoembryonic. In subtropical areas with distinct dry or cool winters, the trees usually flush vegetatively in spring and again in summer. Flowers are normally borne on the spring flushes. In warm humid areas, flushing may be more or less continuous and flowering and hence fruiting occur over much of the year. Fruit set is generally very high, but is accompanied soon after by one or more periods of abscission. Fruit mature after 7 to 8 months. Depending on tree vigour, trees may follow a cycle of "on" and "off" years. Yields may be so heavy in some species that part of or the whole tree dies.

E. Ecological Adaptation

Citrus are grown in tropical areas up to an elevation of 2100 m with no distinct cold period (days below 20°C) and one or more extended wet seasons; subtropical areas with cool dry winters and warm wet summers; and in Mediterranean areas with cool wet winters and dry hot summers. Cropping occurs throughout the year in the tropics but is normally restricted to late summer, autumn, or winter in the other climatic zones. Fruit also mature 1 to 2 months earlier in the tropics. Cultivars selected for one area do not generally perform as well in other locations. A dry period promotes floral induction in some species, although water requirements generally increase from flowering and fruit set to fruit filling. Estimates of crop water use indicate 100 mm is required during a cool month and 250 mm during a hot month.

F. Uses of the Fruit

Citrus have mainly been used as fresh fruit, but substantial quantities are now processed into juice, jams, dairy products, and sweets. There are very large industries based on the export of frozen orange concentrate particularly from South America. The fruit can be used for flavoring many dishes and segments or pieces canned. Citrus are also good sources of pectin, citric acid, and essential oils.

III. Banana

A. Origin, Distribution, and Commercial Importance

Bananas (*Musa* spp.) are thought to have originated in Southeast Asia, possibly in the area between Malaysia, Indonesia, and Papua New Guinea. However, their exact origin is not known and there is much confusion on the ancestry of modern bananas. Cultivated bananas were reported to be first taken to Europe in the 10th century and later to West Africa and South America. Banana now dominates tropical fruit production, along with citrus, and ranges from shifting cultivation, home gardens to extensive corporate plantings. In the tropics they are usually grown at elevations below 1600 m. Countries producing more than 2.0 Mt of *Musa* are Rwanda, Tanzania, Uganda, Zaire, Brazil, Colombia, Ecuador, India, Indonesia, and the Philippines. Many of these countries produce more plantain (cooking banana) than banana, although overall, about two-thirds of the world's production of *Musa* comes from banana. Bananas, notably Cavendish cultivars (AAA group), are important as an export earner for several countries including the Philippines, Malaysia, Honduras, Panama, West Indies, Colombia, and Ecuador. Cultivars for export need a long green life before ripening begins. [*See* BANANAS.]

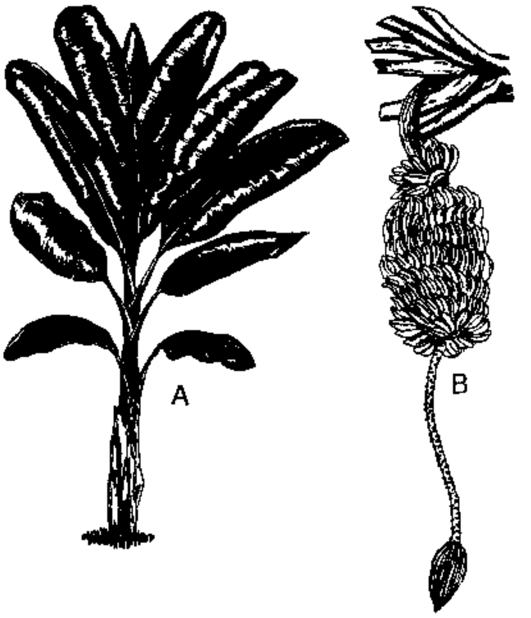

FIGURE 3 *Musa* AAB group cv. Mysore (banana). (A) Young plant (× 1/30). (B) Fruit bunch (× 1/10). [Redrawn by Cathie Menzel with permission from Purseglove, J. W. (1968). "Tropical Crops—Monocotleydons 2," Fig. 25, p. 359. Copyright © 1972 by Longman Group U.K., Harlow, U.K.]

B. Botanical Relations and Cultivars

Banana generally refers to a number of species and hybrids of *Musa* in the family Musaceae. Most edible species of banana are *Musa acuminata* or hybrids between *M. acuminata* and *M. balbisiana*, although no edible forms of the latter species have been found. There are various diploids, triploids, and tetraploids containing different proportions of *M. acuminata* (A) and *M. balbisiana* (B) such as AA, AAA, AAAA, and hybrids AB, AAB, ABB, and ABBB. There are also other species of *Musa* which are economically important as ornamentals or good sources of fiber.

C. Description of Plant (Fig. 3)

The banana plant is a large herbaceous evergreen monocotyledon from 2 to 9 m tall with a thick succulent pseudostem which comprises a series of overlapping leaf sheaths tightly wrapped around each other to form a rigid bundle 20–25 cm in diameter. New leaves originate from the growing point at the top of the underground rhizome and grow up through the center of the pseudostem. Leaves are from 2 to 4 m long and 60 to 100 cm wide and green. Juvenile leaves of many cultivars have maroon patches on the upper surface and are red-purple underneath. A major exception is the ABB group which is devoid of purple pigments. The inflorescence is a terminal spike produced from the tip of the stem after about 25–50 leaves have appeared. The inflorescence is initially a large tight, long-oval purplish bud (not in the ABB group) which later opens to reveal slim nectar-rich flowers covered by thick waxy bracts. There are female flowers at the proximal end and male flowers at the distal end of the inflorescence. Young fruit are initially slender green fingers. The flower bracts are soon shed and fully grown fruit in each cluster become a "hand" of bananas. Mature fruit are green, yellow, or red, from 6 to 35 cm long and 2 to 5 cm wide, and range greatly in shape from oblong, cylindrical, and blunt to triangular, curved, and hornlike. When fruit are ripe, flesh is white, yellow, or red-yellow, firm or soft, and moist or dry. Plantains are normally dry even when ripe. Flavor is mild, sweet, or subacid. Cultivated varieties do not generally have seeds.

D. Growth and Development

Under optimum conditions, vegetative growth is rapid with about one leaf emerging every week. The size of successive leaves increases to a maximum shortly before flowering, when about 30 leaves have been produced. The inflorescence normally emerges 8 to 9 months after planting, longer in the cool subtropics or at higher elevation in the tropics. Fruit are normally harvested 3 to 5 months after flower opening. Side shoots or suckers emerge from buds on the rhizome initially forming a good rhizome and root system and then significant leaf production after flowering of the mother plant. Productivity can be maintained for 10 years or more in some situations before yields start to decline.

E. Ecological Adaptation

Within the latitudes of 30° N and 30° S where bananas are exploited there is a great range in environmental conditions. Growth is best in the warm humid lowland tropics with mean temperatures above 25°–27°C, but growth slows at lower temperatures and there is a longer production cycle. Most cultivars stop growing at mean temperatures below 13°C. Bananas are shallow-rooted and are very sensitive to water deficits. Yields are highest in locations with high average rainfall of 200 mm month^{-1} unless frequent irrigation is available. Yields also tend to be highest in locations with high average humidity but not associated with extended cloud cover. In subtropical areas, lower rainfall in winter is less of a concern, since growth is much slower than in summer.

F. Uses of the Fruit

Ripe bananas can be eaten fresh by themselves or used in fruit salads, mashed and used in dairy or bread products, or even frozen or dried. They can be sliced and cooked whole as a savory or dessert. Plantains or cooking bananas feature strongly in the diets of many people in the tropics and subtropics. They are not suitable for eating out of hand but must be fried or baked whole or mixed with other foods such as coconut milk. They are sometimes mashed or used in soups and stews. Plantains can also be processed into flour.

IV. Mango

A. Origin, Distribution, and Commercial Importance

The mango, *Mangifera indica*, from the family Anacardiaceae is native to Asia. There is a primary center of origin in the Indo-Burma region of South Asia and a secondary center in Southeast Asia. The other economically important member of this family is the cashew. Mango has a long history in India where it has been reported to have been grown for several thousand years. It was distributed to eastern Asia in 400–500 B.C. and to east Africa and the Americas by the end of the 18th century. The mango is now widely grown in the tropics below 600 m and in the subtropics from garden trees to small and large commercial plantings. Fruit are very popular when available. India produces 9.5 Mt, about 60% of the world's crop. Other important producers with more than 0.5 Mt each are Pakistan, Thailand, and Mexico.

The volume of world trade in fresh mango in 1985 was about 90,000 t but is increasing rapidly. The major markets are Hong Kong, Singapore, Japan, the United States and Europe. Thailand and the Philippines are important suppliers into Asian markets. Significant quantities of processed mango are also exported especially from India, which accounts for about 60% of the 30,000 t.

B. Botanical Relations and Cultivars

There are hundreds of cultivars and much confusion about their names even in India. Selection for high quality has been carried out in India for thousands of years, although clonal propagation has only been available for 400 years. Many hybrids have been developed in India and Florida over the past 20 years with better fruit color, thicker flesh, superior flavor, and more regular production. Most of the Indian cultivars are monoembryonic forming seeds with a single zygotic embryo with the seedling not true to type. Southeast Asian cultivars are generally polyembryonic forming seeds with several adventitious embryos in the nucellar tissues, which are true to type as the zygotic embryo is normally suppressed. In some countries, smooth-fleshed cultivars are grown for the fresh market and other more fibrous cultivars for processing.

C. Description of the Plant (Fig. 4)

The mango is a large erect evergreen tree up to 30–40 m high in old specimens. The leaves are borne in rosettes at the tips of branches and are initially yellow, pink, or red becoming dark-green and glossy above and lighter underneath. Mature leaves are 8–40 cm long and 2–10 cm wide. Up to 4000 small green-yellow flowers are borne on terminal panicles. The panicles have a variable proportion of male and hermaphrodite flowers depending on the cultivar and temperature. Fruit vary significantly in size, shape, and color and may be round, oval, or kidney-shaped and up to 4 kg, although normally 300–800 g. The skin is leathery, thick, and dark-green, yellow, or-

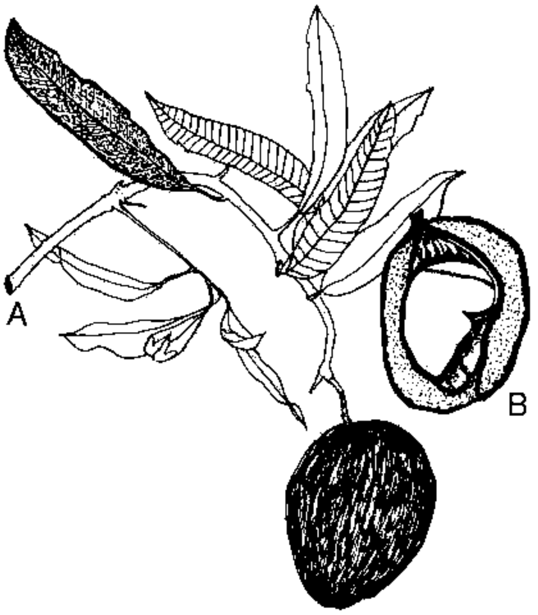

FIGURE 4 *Mangifera indica* (mango). (A) Shoot with fruit (× 1/3). (B) Fruit in longitudinal section (× 1/2). [Redrawn by Cathie Menzel with permission from Purseglove, J. W. (1968), "Tropical Crops—Dicotleydons," Fig. 2, p. 27. Copyright © 1968 by Longman Group U.K., Harlow, U.K.]

ange, or red and the flesh pale yellow to deep orange, smooth or fibrous, acid, sweet, musky and overpowering, or bland. The better flavored attractive cultivars are highly sought after in the market place.

D. Growth and Development

In mature trees, up to four leaf flushes may occur each year depending on environmental conditions, tree management, and crop load, although not all the terminal branches may flush at any one time. Many cultivars will not flower successfully if branches have flushed recently. Panicle and flower development are very rapid, normally taking no more than 30–40 days especially with day temperatures above 25°–30°C. Fruit set is rather poor with less than 1% of hermaphrodite flowers carrying a fruit to harvest even with good disease and insect control. Fruit ripen after 3 to 5 months. Biennial bearing is a problem in many cultivars especially if tree management is poor or if cool weather follows soon after harvest.

E. Ecological Adaptation

Mango is grown in a wide range of environments where temperatures and moisture supply vary considerably. It performs best in climates with dry periods during flowering and fruit ontogeny and rain in summer after harvest. New growth is killed by light frost which limits plantings to coastal areas in cool subtropical locations. Vegetative growth is promoted by warm temperature of 25°–30°C and good moisture supply. Cool winters below 20°C are reported to induce flowering in subtropical areas, although in the tropics moisture stress is thought to be responsible. Cool nights below 12°C around flowering reduce pollination and induce the production of small unmarketable fruit. Rainfall ranges from 750 to 2500 mm year^{-1} in most mango areas. Although mango is reported to survive drought conditions, the effects of moisture stress on fruit production are not fully understood. Water stress during early fruit development increases fruit drop. Stress later during fruit maturation delays dry matter accumulation and leads to ripening abnormalities.

F. Uses of the Fruit

Mangos are generally used as fresh fruit either by themselves or in fruit salads, although significant quantities are processed into canned fruit or used in nectars, juices, jellies, dairy products, and sweets. They can also be successfully dried. Mangos are usually eaten when fully ripe, but are popular as green fruit in parts of Southeast Asia. There is also a large market for mango pickles or chutney (atchar), and in some plantations mangos are harvested green exclusively for pickling.

V. Pineapple

A. Origin, Distribution, and Commercial Importance

The pineapple, *Ananas comosus*, is the most important edible member of the family Bromeliaceae which has over 2000 species, mostly epiphytic and many attractive and economically important ornamentals. It is native to tropical South America, possibly in the area between southern Brazil and Paraguay, where it was domesticated long before the arrival of the Spanish. It was introduced to Southeast Asia in the 1500s and soon after to much of the tropical world. Pineapples are now widely grown up to 30° latitude with production of at least 0.5 Mt in the United States, Mexico, Brazil, China, Indonesia, the Philippines, and Thailand. Processing is very important with about half the world's pineapple production processed.

The pineapple is now one of the leading commercial fruit crops of the tropics with significant exports of canned and fresh product. The volume of canned fruit is about 0.7 Mt year^{-1}. The major suppliers are the Philippines, Thailand, Taiwan, South Africa, Malaysia, and more recently Indonesia. Canned pineapple juice exports are even more important, but there are no reliable figures available. Fresh fruit trade is about 0.5 Mt annually. Leading players in the fresh pineapple trade are Taiwan, the Philippines, Puerto Rico, Mexico, Brazil, Guinea, Ivory Coast, South Africa, and Martinique.

B. Botanical Relations and Cultivars

Pineapple cultivars vary greatly in yield and fruit weight as well as color and flavor of the flesh. The main commercial varieties can be grouped into four types. The Cayenne group grown mostly in Asia, Kenya, and the United States has leaves with spines only at the base and top and cylindrical fruit weighing about 2.5 kg with pale yellow to yellow flesh. The Queen group mainly grown in Australia and South Africa has spiny leaves and fruit weighing 0.9–1.3 kg with crisp golden flesh. Queen types are also low in acid and high in sugar. The Red Spanish group is mainly grown in Central and South America and Malaysia and has characteristics intermediate between those of Cayenne and Queen. Perolera is another important group. While it is grown commercially only in South America, its main use has been as a parent in breeding programs. Various hybrids between the other groups are also exploited commercially.

C. Description of the Plant (Fig. 5)

The pineapple is a perennial or biennial herb usually about 0.5–1.5 m in height, although occasionally taller. Plants have a short stocky stem and a rosette of waxy tough leaves 0.5–1.0 m long. The inflorescence is short with up to 200 bluish-purple sessile flowers each subtended by a pointed bract. After flowering, individual fruit join together to form a conical-shaped compound juicy fleshy fruit up to 20–30 cm long. The skin is tough, waxy, and dark-green, yellow, or orange-yellow when the fruit is ripe and the flesh white to yellow, juicy and acid, subacid, sweet, or bland depending on cultivar, season, and maturity. Fruit are normally seedless due to self-incompatibility unless the flowers have been cross-pollinated by hand with pollen from a different group.

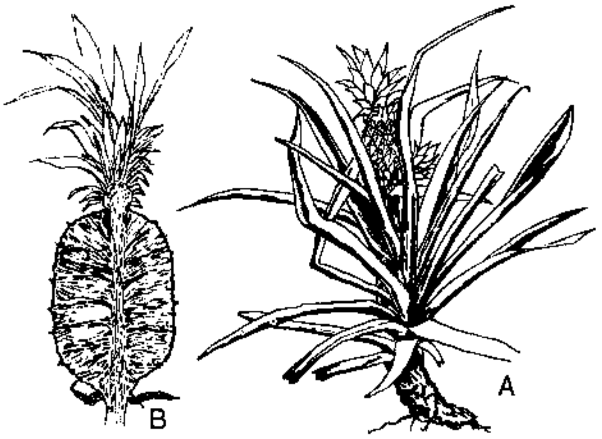

FIGURE 5 *Ananas comosus* (pineapple). (A) Plant with a young fruit (× 1/10). (B) Fruit in longitudinal section (× 1/4). [Redrawn by Cathie Menzel with permission from Purseglove, J. W. (1972). "Tropical Crops—Monocotleydons I," Fig. 10, p. 83. Copyright © 1972 by Longman Group U.K., Harlow, U.K.]

There are generally no natural pollinators in most countries that grow pineapples.

D. Growth and Development

Pineapples are normally propagated by crowns which are removed prior to processing or by vegetative shoots which arise from the base of the fruit as it develops (slips) or from the base of the plant (suckers).

Plants can produce up to one leaf per week under ideal conditions. After floral induction the stem elongates and enlarges near the growing point and forms a tight cluster of flowers. The stem continues to grow at its apex and forms a crown of compact leaves. The first flower opens about 50 days after induction and anthesis continues for 20–40 days. Planting to harvest takes about 15–18 months in tropical areas and 20–23 months in subtropical area with a distinct cool season. One or more ratoon crops can be produced from suckers at the base of the plant thus reducing planting costs and shortening the production cycle.

E. Ecological Adaptation

The pineapple is generally grown at low elevations from 0° to 30° latitude when day temperatures range from 20°–35°C, although some commercial plantings are found up to 2300 m in the tropics. The crop cycle is shorter in the lowland tropics, while in cool areas fruit may be too acid for the fresh market for much of the year or be unmarketable due to discoloration of the flesh (endogenous browning). Sugar levels are less important for processed fruit as they can be readily adjusted in the factory. In hot dry area there can be problems with sunburn of fruit. The plant is also sensitive to frost although it will tolerate cool nights for a short period. Pineapples are tolerant to intermittent drought but are susceptible to root rots. They are grown in areas with rainfall from 650 to 3800 mm year^{-1}. This rainfall should ideally be spread throughout the year, since most plantations are not irrigated. In cooler subtropical areas, winter rainfall becomes less important because lower average temperatures markedly reduce growth rates.

F. Uses of the Fruit

Pineapples are often used fresh particularly in tropical fruit salads. They can also be processed into juice, jams, yoghurt, ice cream, or sweets. A significant proportion of the crop is usually canned into slices, cubes, or crush. Fruit slices can also be successfully dried.

VI. Papaya

A. Origin, Distribution, and Commercial Importance

Papaya, *Carica papaya*, is a member of the family Caricaceae native to tropical South America possibly in the area between Mexico and Central America. It was brought to the Caribbean and Southeast Asia during the 16th century by Spanish explorers and quickly spread to India, Oceania, and Africa. Production of more than 0.2 Mt occurs in Brazil, Mexico, Zaire, Thailand, Indonesia, and India.

The fruit are delicate, are easily bruised, and succumb to pre- and postharvest diseases, and therefore lag behind other species such as citrus, banana, and pineapple especially in export markets. Processing is also less developed. Much of the crop is grown in home gardens which are not included in official estimates of production. The tree is also susceptible to a wide range of preharvest pests and diseases which reduce fruit quality and the life of a planting. Often orchards bear well for only 2 to 3 years. The short life of plantations reduces average yields and increases growing costs. One advantage is that the tree is fast growing and bears early. Papaya can thus be interplanted as a temporary crop in orchards with slower growing longer-lived fruit trees such as mango. There can, however, be problems with spray management in mixed plantings.

B. Botanical Relations and Cultivars

There is much variation in the size, shape, and quality of fruit and productivity even in commercial orchards because of outcrossing which gives highly variable seedling populations. Fruit from hermaphrodite or bisexual flowers are usually cylindrical or pyriform with a small seed cavity and thick firm flesh which transports well. In contrast, fruit from female flowers are nearly round or oval-shaped with thin flesh. Some industries have used hand pollination to maintain a selected strain particularly when material from overseas has been incorporated. Care must be taken to avoid cross-pollination from inferior local material. Significant breeding efforts have been made in Hawaii, Australia, Taiwan, Thailand, Malaysia, and the Philippines. Firm flesh and resistance to soft rots have been important considerations in these breeding programs.

C. Description of the Plant (Fig. 6)

Papaya is a fast growing herb-like tree reaching up to 2–10 m in vigorous 3- to 5-year-old specimens. It is usually unbranched unless the growing point is injured. The stem is hollow, green, or deep purple with a thick base. The leaves emerge directly from

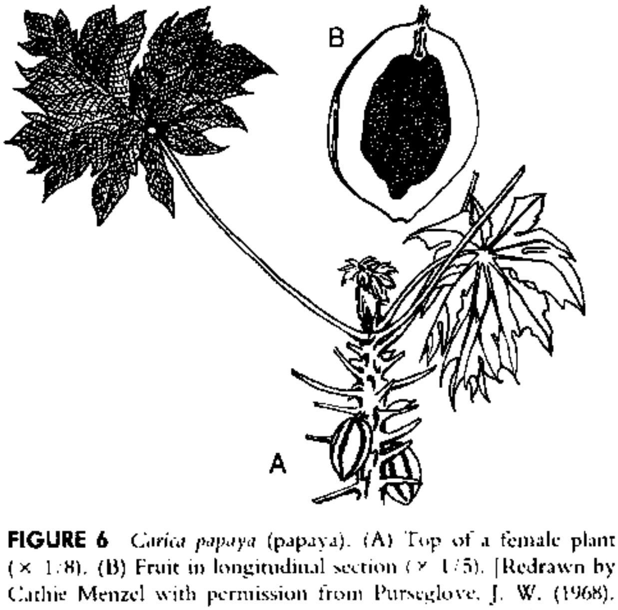

FIGURE 6 *Carica papaya* (papaya). (A) Top of a female plant (× 1/8). (B) Fruit in longitudinal section (× 1/5). [Redrawn by Cathie Menzel with permission from Purseglove, J. W. (1968). "Tropical Crops—Dicotleydons," Fig. 5, p. 47. Copyright © 1968 by Longman Group U.K., Harlow, U.K.]

the upper part of the stem with the petiole up to a meter long and the leaf blade deeply divided into 5–11 main segments usually about 25–75 cm in diameter. Both the stem and leaves contain a milky latex. The flowers are fleshy, waxy, and fragrant and have five petals. Some plants bear only female or hermaphrodite flowers, others only male flowers (dioecious plants). There may also be monoecious plants bearing both male and female flowers. Fruit are melon like, oval to nearly round, 7–50 cm long, weigh up to 9–10 kg, although normally 1–3 kg. The skin is waxy and thin, but tough. When the fruit is green it is rich in white latex. Ripe fruit have a light to deep yellow skin with soft yellow, orange, pink, or red flesh. There are numerous small black seeds coated with a transparent gel attached to the flesh by white fibrous tissue.

D. Growth and Development

Papayas are normally grown from seed. Cuttings are sometimes exploited and have high early yields but are susceptible to wind damage. With controlled pollination the ratio of offspring in seedling populations is predictable: a female × male cross gives 50% female and 50% male; female × hermaphrodite gives 50% female and 50% hermaphrodite; while hermaphrodite × male gives one-third female, one-third hermaphrodite, and one-third male. Growers normally plant three to five seedlings per site and thin out plants once they have flowered. If a hermaphrodite planting is desired, only the vigorous hermaphrodite plants are retained. For female plantings, a ratio of 1 male:10 females is essential for satisfactory production. There are a few industries partly based on clonal propagation by cuttings or tissue culture.

Seedling growth is initially rapid particularly under warm moist conditions with up to two leaves appearing each week. Once fruiting commences, the rate of stem extension and leaf initiation slows. Yield is related to the number of flowering nodes and the size of the supporting leaf area.

E. Ecological Adaptation

Papayas grow in tropical and subtropical locations up to 32° latitude, where day temperatures range from 20° to 35°C. In the tropics, they are normally found up to 1600 m elevation, above which killing frosts may occur. Frost also restricts production generally to coastal areas in subtropical locations. Fruiting is related to new growth; hence, maximum yields are recorded in the warm tropics. In the cool subtropics both leaf and fruit growth are reduced and the production cycle is extended. Cool weather also reduces the sugar and flavor components of the fruit. Quality is superior in the tropics. Even distribution of rain of at least 1200–1500 mm year^{-1} is required for optimum production, unless irrigation is available. Cycles of dry and cool weather followed by warm wet weather which encourage rapid growth have been associated with dieback or decline in subtropical Australia.

F. Uses of the Fruit

Fresh papayas are generally eaten with orange, lemon, or lime juice or used in fruit salads. They are a favorite breakfast in many cultures. Papaya can be used in drinks, jams, candies, and crystallized fruit. Chunks are used in canned fruit salads, but do not retain the texture and flavor of fresh fruit. Firm fruit can also be baked. In some areas, papaya is grown in sizeable plantations for the extraction of papain, an enzyme collected from the latex of green fruit which has several uses in the food, beverage, and pharmaceutical industries.

VII. Avocado

A. Origin, Distribution, and Commercial Importance

The avocado, *Persea americana*, from the family Lauraceae is believed to have originated in Central America, possibly in the area between Mexico, Guatemala, and Honduras. It was cultivated in much of central and northern South America long before the arrival of Europeans. Avocado was initially sent to the West Indies in the late 1600s and quickly spread to the rest of South America and then to Asia and Africa. It is now found growing from the tropical lowlands to cool subtropical areas, many Mediterranean zones, and even in some temperate locations. Major producers with more than 0.1 Mt are Mexico, the United States, Dominican Republic, and Brazil. It is less popular in Southeast Asia, Oceania, and Africa.

Significant quantities of fresh fruit are exported from Israel, Spain, South Africa, and the United States into the U.K., France, and other E.C. countries. Demand for fruit is steadily increasing especially in Europe.

B. Botanical Relations and Cultivars

Three races are generally distinguished in order of increasing tropical adaptation: Mexican, Guatemalan, and West Indian. West Indian types contain less oil in the fruit (3–10% vs 10–30% for the other groups) and are generally considered inferior in taste and quality, lacking the true "nutty" flavour of the other groups. They also have a leathery, pliable skin, and smooth flesh. However, the West Indian types are more salt tolerant. Guatemalan races have thin to very thick skin and granular flesh. The Mexican group has thin soft skin which clings to the flesh. The races hybridize readily and hence a range of cultivars adapted to cool, dry Mediterranean climates up to warm moist tropical lowland conditions are available. Various hybrids are now commercialized and clonally propagated. The major export cultivars are Hass and Fuerte.

C. Description of the Plant (Fig. 7)

Avocado may be an erect or spreading evergreen tree up to 18–20 m tall with thick sturdy branches and a large trunk. The leaves are dark-green and glossy on the upper surface and whitish on the underside, and usually about 5–40 cm long. Those of the Mexican race have a strong aniseed smell when crushed. The small pale green-yellow flowers are borne on short panicles on terminal branches. The fruit are pear-shaped or nearly round up to 20–35 cm long and 15 cm wide. The skin may be thick or thin, smooth or rough, cling to or easily separate from the flesh, and range from yellow-green to maroon, purple, and black. Fruit weigh up to 1 kg but usually 300–500 g. The flesh is yellow-green, buttery and nutty, sometimes granular, or watery and bland. The size of the ivory seed and hence flesh recovery varies greatly with the cultivar.

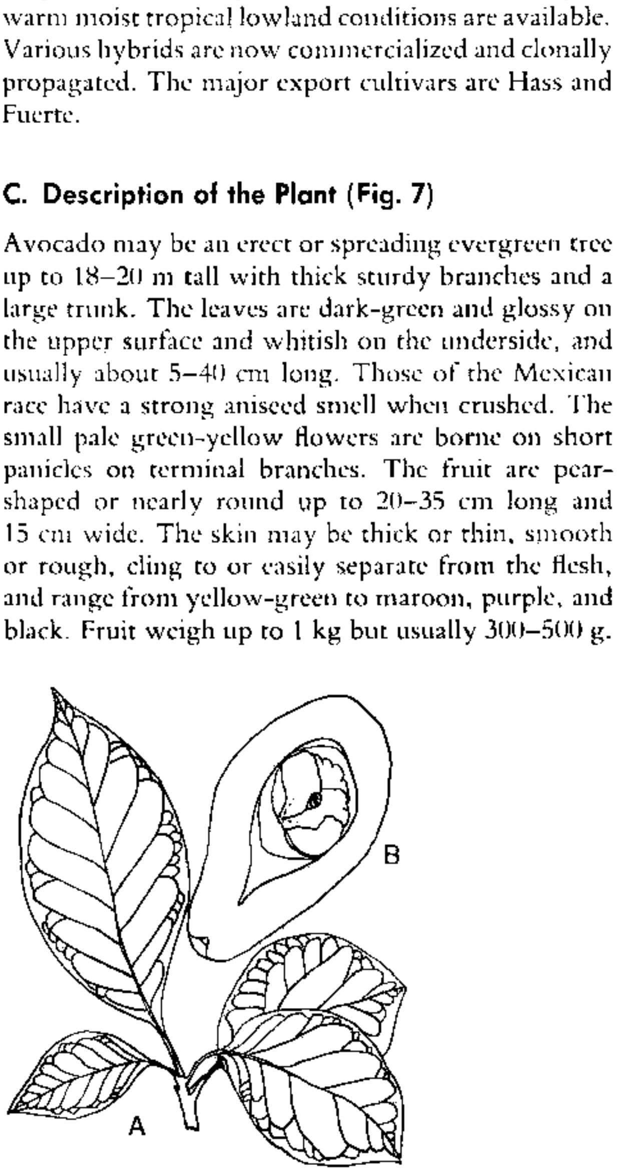

FIGURE 7 *Persea americana* (avocado). (A) Leafy shoot (× 1/2). (B) Fruit in longitudinal section (× 1/2). [Redrawn by Cathie Menzel with permission from Purseglove, J. W. (1968). "Tropical Crops—Dicotleydons." Fig. 29, p. 195. Copyright © 1968 by Longman Group U.K., Harlow, U.K.]

D. Growth and Development

Leaf growth in mature trees generally occurs in synchronized flushes promoted by warm temperatures of 25°–30°C and good moisture supply. Leaves have a short life normally less than one year. Trees usually have vegetative flushes in spring and summer in the subtropics with floral induction occurring at the end of the summer flush and fruit set concurrent with the spring flush in indeterminate flowering branches. In determinate branches, shoot growth ends with flowering. In tropical locations, flushing is more frequent and floral induction can occur several times during any dormant nonflushing period. Floral development is rapid with induction to anthesis normally taking 8 to 10 weeks, less in tropical climates. Anthesis takes 2 to 3 weeks in warm areas and 2 to 3 months in the cool subtropics. Fruit set is normally very heavy but two periods of abscission occur in late spring and summer. In subtropical locations especially at elevation, fruit set can be very poor in early cultivars flowering during cool weather in spring. The interplay between the growth flushes with production is complex. Young flushes compete strongly with the developing fruitlets but high rates of carbon assimilation and hence a sizeable leaf area are required to fill the fruit. Avocados take 6–12 months to mature and are a heavy drain on the tree due to the high oil content of the fruit. Ripening only commences once fruit are harvested and thus a single block of one cultivar in an orchard can be successfully marketed over several weeks. Fruit take 7 to 10 days to ripen at room temperature. Ripening can be delayed for several weeks with storage at 7°C.

E. Ecological Adaptation

The original avocado tree was adapted to the rainforests of the humid tropics and subtropics of Central America. Commercial production, however, has now spread to many other environments. West Indian types yield best in pantropical areas with days of 28°–36°C and high humidity especially around anthesis. Trees may be damaged at 1°–2°C. The Guatemalan races originating at higher elevation in Central America are successful in cooler areas such as coastal California. The Mexican races are the most cold tolerant and will survive short periods below freezing. Day temperatures of 25°–30°C and high humidity are optimum. The Mexican races were the source of many of the earlier commercial varieties in the main avocado growing areas of California, although about 90% of production is now based on Hass (Guatemalan). Other important cultivars are Pinkerton (mainly Guatemalan) and Reed (Guatemalan). Californian avocados are mostly grafted onto Mexican rootstocks.

Avocado cannot survive excessive soil moisture or even temporary water-logging especially when under pressure from root rot, *Phytopthora cinnamomi*. Hence, sites with poor drainage are best avoided for commercial production. Water supply is particularly critical during the flowering and fruit set period and up to the summer drop. Trees are sensitive to excess salts. Water quality should be checked before planting.

F. Uses of the Fruit

The fruit has a long history in the diet of Central Americans, being mainly used as an uncooked savory mixed with herbs and spices, but can also be used to enhance the presentation and consumption of many foods. More recently the oil has been used in cosmetics and soaps, but is generally too expensive to be used as a cooking oil.

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Tropical Grasslands

W. D. PITMAN, *University of Florida*

Glossary

Community Assemblage of organisms occupying a common environment and interacting with each other

Formation Major unit of vegetation representing the natural potential of an area under the ultimate control of climate; tropical grasslands and tropical rain forests are examples

Herbaceous Nonwoody

Herbivory Process of feeding on plant herbage

Landscape Ecological unit, such as a watershed or drainage basin, typically consisting of different communities or even formations which do not function independent of each other

Pastoralist Individual who derives his living from grasslands through grazing livestock; this term is typically applied to those living in close contact with the grassland ecosystem, such as the pastoral nomads

Rangeland Those portions of the grassland formations which are managed as natural ecosystems: that is, using ecological principles rather than agronomic approaches

Savanna Grassland with scattered trees or shrubs, in a distinctly seasonal climate of alternating wet and dry periods; the term savanna has been used for a number of different plant communities and landscapes with various specific definitions in the literature

Succession Process of change within communities which eventually leads to a somewhat stable but dynamic community capable of maintaining itself under the prevailing conditions

Tropical Grasslands are defined by vegetation type and either location or climate. Tropical grasslands may be defined as plant communities dominated by grasses (plants of the family Gramineae) in the tropics. Thus, by definition, tropical grasslands occur in the tropics, the zone between the Tropic of Cancer (23½° N) and the Tropic of Capricorn (23½° S). Grasslands at higher latitudes are excluded. Grasslands at high elevations within the tropics, such as the temperate and alpine grasslands of the Andes mountains in Peru, are considered tropical grasslands based on this definition. Alternatively, tropical grasslands may be defined as plant communities dominated by grasses in regions with tropical climates (and may even be extended to regions with subtropical climates that support grassland communities characteristic of the tropics). In this case, the high elevation areas within the tropics which are subjected to temperate or alpine climates are excluded. The areas with tropical (and subtropical) climates, which typically extend to higher latitudes in coastal zones, are included. The choice of definition depends on the purpose. For geographical purposes, the former definition could often be more useful. For agricultural purposes, the latter definition would often be most useful.

I. Description

Tropical grasslands include the native grass formations which comprise the tropical rangelands and much smaller areas of planted pasture along with naturally occurring secondary grasslands including those composed of aggressive, weedy grass species which are often abandoned and considered waste lands. As with other grasslands of the world, a number of plant families in addition to the Gramineae are typically included in the plant communities of tropical grasslands. As with other grasslands, the majority of these nongrass plants are herbaceous species. In contrast to the temperate grasslands, which are characterized by the absence of trees on the extensive plains and prairies, tropical grasslands are typified by a landscape of grass with scattered trees. In fact, tropical grasslands include a range in vegetation types from grasslands with essentially no woody plants through the complete continuum of increased woodiness to woodland conditions where an overstory canopy of woody plants prevents development of a continuous grass cover.

Tropical grasslands which occur in climates of distinct seasonal rainfall and include characteristic woody species are commonly called savannas. In some cases, competition for limited moisture maintains the balance between grasses and woody species, with the extensive fibrous roots of grasses at an advantage with limited shallow moisture and woody plants benefiting from deep moisture. Fire, either natural or anthropogenic, often limits development of woody plants and maintains the grass dominance. Such savannas occur over a wide range of rainfall conditions and geographic locations. The plant species present differ with both the moisture conditions and location. Under high rainfall conditions, extremely tall-growing grasses such as bamboo (subfamily Bambuseae) and elephantgrass (*Pennisetum purpureum*) can form dense grass stands with interspersed remnant trees where the natural forest has been disturbed. As rainfall decreases, grasses of shorter stature dominate with height of associated trees also less. Density of the grass stand becomes less under semi-arid conditions with shrubs comprising the woody component of these drier grasslands. The short, sparse grasses where tropical grasslands merge with deserts may appear similar to the temperate short-grass prairie or steppe. Tropical grasslands in similar rainfall zones have a similar general appearance regardless of location. However, species of both the grasses which dominate these grasslands and the associated trees differ with somewhat similar appearing but distinct species in the extensive tropical grasslands of South America, Africa, and Australia.

II. Distribution

Tropical grasslands occur naturally in the zone between the tropical forests and warm deserts. The largest expanse of tropical grassland occurs in Africa. This grassland extends across West Africa from the Sahara Desert southward to the Congo forest region and eastward to the Ethiopian Highlands. It then extends around the eastern extent of the Congo forest region near Lake Victoria and across southern Africa to the Kalahari Desert. Within this grassland region are considerable areas of woodland, particularly an expansive region between the tall-grass savanna just south of the Congo and the short-grass savanna immediately north of the Kalahari. Much of this African grassland includes areas where cultivated fields, woodlands, and grassland form a mosaic pattern across the landscape. Additional extensive tropical grasslands occur in western Madagascar.

Extensive grassland regions also occur both north and south of the Amazon forest of South America. Tropical grasslands also occur in Australia between the northern tropical forest and the central desert. Additional natural tropical grasslands occur in tropical Asia including the Indian subcontinent, often as relatively small areas within forested and cultivated landscapes. Grasslands are also found interspersed within forested and cultivated landscapes in Central America. As in Africa, the South American and Australian grasslands border both tropical forest and other woodland zones. These other woodlands differ from forest in that, despite dominance by woody species, a closed upper tree canopy does not develop to exclude herbaceous species including shade-tolerant grasses. Thus, there is not a distinct separation between these tropical woodlands and grasslands, and the dominance of either woody plants or grasses, especially in the transition zone, is often determined by factors other than climate and soil, such as fire and biotic effects.

Only a portion of the existing tropical grassland area (estimated to total around 30 million km^2) is generally considered to represent the potential plant community. This has been suggested to include the rainfall zone of about 200 to 600 mm across Africa below the Sahara and edaphically determined grasslands of distinct wet and/or dry conditions in Africa and South America. The existence of a tropical grassland climate has been disputed. Perhaps gradations of forest to woodland to shrubland and finally desert represent the vegetation potential of tropical climates, with occurrence of stable grasslands dependent upon edaphic, biotic, fire, or other constraints to development of woody plants.

Subtropical grasslands are found between the Australian central desert and the east coast, east of the

Kalahari Desert in southern Africa, in the western portion of southern Madagascar, east of the Andes in southern South America, in India, and in North America extending from northeastern Mexico into the southern-most portion of Texas with an isolated area in the Florida peninsula.

In the subtropics and at higher elevations in the tropics where a distinct cool season occurs, rainfall primarily restricted to the cool season favors woody, deep-rooted plants over the warm-season grasses so that a zone of grassland between forest and desert does not occur without prior disturbance of the woody plants. In such environments, the advantage of efficient water uptake by fibrous-rooted grasses is lost because they are often dormant when moisture is available. In these situations, the natural vegetation in the intermediate zone is typically brush comprised of decreasing density of thorny shrubs of decreasing height as rainfall decreases from the woodland zone to desert.

III. Additional Characteristics

In addition to the expected intermediate annual rainfall levels between those of tropical rainforests and deserts, seasonal rainfall distribution is characteristic of tropical grasslands. A distinct dry season is a key aspect of fire-induced grasslands. In extreme instances, moisture conditions can alternate from flood to essentially complete loss of moisture available within the rooting zone of herbaceous plants on an annual basis. This distribution, more than average annual amount, is a major factor in determining the range of natural grasslands in the tropics. Soils, as they affect moisture conditions and plant root growth, also are determining factors in the occurrence of natural grasslands. Unfavorable soil chemistry and low fertility characterize extensive tropical grasslands, especially in South America, but whether these limitations or anthropogenic effects ultimately restrict woody species in humid environments is still not certain.

The transition from grassland to desert on a regional scale corresponds closely with decreasing rainfall. On a smaller scale within the transition zone, soil and herbivory are important factors. In such arid and semi-arid climates, saline and sodic soils limit many grassland species and enhance the effects of moisture limitations. Excessive herbivory in arid and semiarid climates contributes to loss of herbaceous vegetation and can contribute to the conversion of grassland to desert.

At the other extreme, moisture limitations to the growth of woody species can be determinants of the extension of natural grasslands into the more humid tropical region. Again, other factors including soil, geomorphology, rainfall distribution, and herbivory contribute to the determination of the stable vegetation. As annual rainfall amount increases, extent of moisture limitations during the dry season may be a limiting factor to development of woody vegetation. Soil factors such as low nutrient status, low pH, high aluminum levels, and impediments of deep root development can also limit woody vegetation and contribute to the range of tropical grasslands. Effects of herbivory depend on which plants are defoliated, as well as the frequency, intensity, and season of defoliation. The more commonly observed effect is a seasonal overutilization of herbaceous vegetation contributing to the opportunity for establishment of woody species in grassland ecosystems which receive sufficient moisture to support woody plants. An opposite effect in the transition zone between grassland and forest or woodland is provided by fire. Burning, when sufficient fuel is provided by herbaceous vegetation, can prevent establishment of woody species and maintain the grassland vegetation.

IV. Anthropogenic Influences

From an ecological viewpoint, it is of considerable interest to distinguish between the zones of potential grassland and those of other formations. The current range of these grasslands has been greatly affected by man. Grasslands have been lost to desertification due to attempts at cultivation and overgrazing in the more arid grasslands. Similar activities of man have degraded grasslands in higher rainfall regions as erosion and brush encroachment have resulted from overgrazing and inappropriate cultivation attempts. On the other hand, clearing of forest and burning maintain grasslands in areas where forest naturally occurred. It is difficult to separate anthropogenic effects from natural development in some situations where grazing and cultivation have occurred over extended historical periods. It is even more difficult to distinguish between the natural fire-maintained savannas and some of the fire-maintained savannas that are due to man. [*See* DESERTIFICATION OF DRYLANDS.]

Some of the anthropogenic grasslands are readily distinguishable from the natural vegetation which characterizes grassland formations. Such secondary grasslands, those developing on sites following disturbance of the stable vegetation, can occur naturally or in response to activities of man. The natural secondary grasslands typically possess the characteristic of great diversity of plant species and succession, or change in plant populations over time, toward a diverse, dynamic but stable vegetation formation. Some disturbed sites in humid to subhumid zones from tropical Asia to subtropical America may be dominated by dense, persistent monocultures of the weedy grass *Imperata cylindrica*. Activities of man have spread this grass and provided opportunities for its establishment and dominance by disturbing existing vegetation. On slightly drier sites where productive grasslands have been continuously overgrazed by man's excessive concentration of livestock, the grazing tolerant grass *Bothriochloa pertusa* has formed a dense monoculture of rather low productivity in various tropical locations. Although such grassland areas are atypical, these examples illustrate how unintended responses to man's activities can sometimes result in stands of less desirable species for either livestock production or environmental quality. Such degraded sites offer opportunities for grassland improvement to benefit agricultural productivity or other uses, and these opportunities occur in some areas where such improvement is of greatest urgency.

Wherever tropical grasslands occur, it is unlikely that the current extent corresponds with the area of potential grassland as determined by climatic and edaphic conditions. Most of the humid tropical grasslands are anthropogenic in nature. Such areas as the tall-grass savannas which occur at abrupt boundaries with tropical forests are for the most part anthropogenic due to the effects of such activities as shifting cultivation, harvest of trees, and repeated burning which restrict redevelopment of forest or woodland communities.

Considerable evidence indicates that grasslands previously extended into present desert regions. While climatic change may be associated to a degree, it is evident that disturbance of grasslands by continued overgrazing and attempts at cultivation on sites with inadequate moisture have contributed to, or at least accelerated, the rate of desertification in some regions. In addition to loss of arid grasslands to environmental degradation, in the more humid extent of the tropical grassland zone, extensive areas have been converted to cropland.

V. Productivity

Productivity can be considered in the sense of primary production, that is the conversion of solar energy into biomass by plants through the process of photosynthesis. This primary production over the extent of tropical grasslands is determined on a broad scale by moisture. In the more humid range of tropical grasslands, extremely high production potentials extend up to 2 kg/m^2 of dry herbage annually under the most favorable conditions. On the other extreme, only a few grams of biomass per square meter may be produced in dry years in the drier extension of tropical grasslands. Along with average annual amount of moisture, fluctuations from year to year, distribution within the year, and soil factors affecting moisture retention and availability to plants affect the botanical composition of grasslands. This botanical composition, affected by previous moisture regime, affects potential productivity. Moisture at a given time affects the attainment of this previously set potential productivity.

Within moisture regimes, soil factors, especially fertility, further determine production potential. Tropical soils in areas of high rainfall are often highly leached, resulting in low fertility with associated chemical imbalances. Extensive grasslands in tropical South America are limited in productivity due to highly leached, infertile soils. [*See* SOIL FERTILITY.]

Another major determinant of productivity is degree of defoliation during the growing season. Newly expanded grass leaves in the upper canopy are the primary site of photosynthesis. As grass leaves age, they senesce and become less efficient in the use of solar energy for plant growth. The upper, young leaves are typically the most palatable and nutritious to grazing animals, and these leaves are normally removed first when a grassland is subjected to grazing. Thus, grazing can restrict primary production to levels below the climatic and edaphic potential. In some specific situations grazing has been found to increase grass production through a stimulation of rapid regrowth. Repeated overgrazing or selective grazing among plant species can change the botanical composition and/or plant density and reduce the future potential productivity.

Another aspect of grassland productivity is the support or production of grazing animals. The world's major grasslands are important areas of livestock production. Tropical grasslands on fertile soils in humid regions may support up to three to four mature cows per hectare during the growing season. The less productive grasslands in dry regions may require up to 10 hectares to support one cow for an even shorter growing season. Thus, ranching and even more intensive enterprises of livestock farming, involving annual forage crops for seasonal use, have developed in humid grassland regions. In arid grasslands, the ancient nomadic systems and rather recently expanded transhuminance are still major means of utilizing the resource for domestic livestock production in some regions.

In Africa, primary production of grasslands is much more efficiently harvested by native wildlife populations than it typically is by domestic livestock. Two to three times as much animal biomass as typically produced by domestic livestock is suggested as the potential for native wildlife populations in some grasslands. This is associated with the specialized diets of the diverse native herbivores with various herbs, forbs, and woody species consumed resulting in efficient harvest of the total grassland production. Domestic livestock generally consume selected grasses and associated plant species. [*See* TROPICAL PASTURE DEVELOPMENT.]

VI. The Tropical Grasses

In general, tropical grasslands are characterized by grasses of the subfamily Panicoideae in contrast to temperate grasslands where species of the subfamily Festucoideae predominate. At high elevations in the tropics, grassland areas above the tree line are often similar to temperate grasslands and consist primarily of Festucoid species. Occurrence of the Panicoid grass, *Pennisetum clandestinum* (kikuyu grass), along with Festucoid species is characteristic of the high-elevation grasslands of Africa. These high-elevation grasslands represent only a very small portion of the area of grasslands in the tropics, with an extended range in the Andes of South America and isolated peaks in East Africa and the Pacific islands.

While the subfamily Panicoideae predominates in tropical grasslands, the subfamily Eragrostoideae also provides a substantial portion of the tropical grassland species. In addition to genera such as *Cynodon* and *Chloris* which occur throughout a range of tropical rainfall zones, the number of species of Eragrostoideae and their dominance increase with increasing aridity. This increase in dominance of Eragrostoideae with increasing aridity occurs in tropical, subtropical, and warm temperate regions.

Both the Panicoideae and Eragrostoideae subfamilies are characterized by photosynthesis involving the C-4 photosynthetic pathway in contrast to the C-3 photosynthetic pathway of the Festucoideae. Four-carbon compounds, malic and aspartic acids, are the initial products of the C-4 photosynthetic pathway in contrast to the three-carbon phosphoglyceric acid from the C-3 photosynthetic pathway. Additional anatomical and physiological differences between plants with these contrasting processes of photosynthesis contribute to substantially higher potential dry matter production for C-4 plants than for C-3 plants in warm climates which receive high levels of solar radiation.

Within the more humid tropical grasslands, where the subfamily Panicoideae predominates, the tribes Paniceae and Andropogoneae are of special significance. Some individual species of the tribe Paniceae are particularly aggressive with high growth potentials and high nutrient requirements. These include species of the genera *Brachiaria, Digitaria, Melinis, Panicum, Paspalum, Pennisetum,* and *Setaria,* which are often among the early colonizers of disturbed sites. As soil fertility decreases, which is characteristic of some tropical regions and especially of eroded and leached sites arising from disturbed woodlands and abandoned fields, species of the tribe Andropogeneae begin to increase. These grasses, including species of *Andropogon, Bothriochloa, Dichantium, Hemarthria, Heteropogon, Hyparrhenia, Schizachyrium, Sorghum, Themeda,* and *Tripsacum,* are typically efficient in the use of soil nitrogen. Thus, while they are not generally as productive on fertile sites as the Paniceae species, they may be more productive or at least more stable on infertile sites. The slower growth rates, which often correspond with increased cell wall production, combine with efficient nitrogen use, which often provides low herbage nitrogen concentrations, to produce a less digestible, lower protein herbage at plant maturity. Thus, mature grasses of the tribe Andropogoneae in the humid tropics are often of lower forage quality than those of the tribe Paniceae. These characteristics of tropical grasses, which reflect soil fertility, are major determinants of the nutritive value of these grasslands for grazing animals.

VII. Use and Management

The major use of tropical grasslands throughout the world is for the production of domestic livestock. The natural diversity typical of tropical grasslands provides sources of food and cover for a great variety of wildlife in the various regions of the world. Considerable areas in Africa are devoted primarily to provision for wildlife populations.

Management of natural grassland typically involves lower inputs than required for planted pastures. Fire is often a key aspect of this extensive management, with burning used to control woody plants, remove old herbage growth, and stimulate new regrowth.

Development of watering facilities for livestock is often a key aspect in the improvement of grassland utilization especially in drier areas or during the dry season. Manipulation of grazing through control of livestock is often the primary means of extensive grassland management. Such intensive practices as grass planting, fertilization, irrigation, and pest control are generally not viable options on the natural grasslands of the tropics due to economic and ecological constraints. Exceptions include the control of woody plants with hand labor, selective herbicides, or mechanical means in specific situations.

Approaches to the manipulation of grazing livestock to produce grassland improvement on temperate rangelands have been evaluated for much of this century. Similar evaluations of responses to grazing on tropical grasslands are much more recent and less conclusive. On the native tall-grass prairie of temperate North America, effects of grazing can be rather reliably predicted. The season of grazing, length of the grazing period, and length of time protected from grazing, along with grazing pressure and mix of the animal species (cattle, sheep, and/or goats) can affect both productivity and botanical composition of these grasslands. The specific plants which are favored with various grazing schemes are somewhat predictable, since the grazing selectivity of livestock and responses of individual plants to grazing have been extensively studied on the North American prairie. [*See* RANGELAND GRAZING; RANGELAND PLANTS.]

A perhaps unique and fortuitous phenomenon of the North American tall-grass prairie facilitated early approaches to grazing management. The stable grassland community is comprised of productive, palatable grasses, characterized by upright growth with growing points elevated relatively early in the development process. This morphology and palatability contribute to vulnerability of these grasses to stand loss from heavy grazing pressure. Thus, under excessive utilization, less palatable and generally less productive grasses increase, and the value of the rangeland for livestock grazing decreases. Further continuation of excessive grazing then leads to extensive loss of most of the palatable grasses, resulting in a sparse cover of grasses, invasion by weedy plants, increased soil erosion, and low levels of herbage and livestock production. Simple surveys of the vegetation over time allow trends in botanical composition, resulting from the combination of grazing and environmental conditions, to be detected. Thus, undesirable trends in condition of this rangeland can be detected, and appropriate modifications in grazing (stocking rate, season and frequency of use, livestock species, etc.) can be made to favor the desired grasses. [*See* RANGELAND MANAGEMENT AND PLANNING.]

Similar approaches to grazing management of tropical grasslands have been widely promoted in the past. They have generally not been successful. A number of factors are involved. A large part of the current tropical grasslands exist where the stable vegetation formation, without manipulation by man, is woodland or forest. Regardless of grazing management, some control of woody plants will be required to maintain grassland on many of these woodland and forest sites. Also, the grasses which comprise the stable plant community on low-fertility tropical soils are not necessarily the most nutritious or palatable plants. With release of nutrients from burning and/or in animal waste from initial heavy grazing, they also may not be the most productive. Thus, the stable plant community may not be the most desirable for high herbage production or nutritive value. However, short-term benefits of the more productive, higher quality grasses may lead to a degraded condition for a much longer time if undesirable plants subsequently proliferate as nutrients are lost to leaching, erosion, and volatilization. Since many of the grasses which dominate the stable plant communities in these tropical grasslands are poor seed producers and seedling vigor of these grasses is often not good, recovery of degraded tropical grasslands even with the most favorable grazing system may not occur within the time constraints required for management decisions. Extensive areas of tropical grasslands in arid and semiarid regions which have been subjected to long periods of grazing and repeated droughts are now dominated by annual plants rather than the more stable perennial grasses. Current utilization of these grasslands often emphasizes the efficient harvest of available herbage by grazing livestock rather than emphasizing the plant community and soil stability. Such emphasis on obtaining available, immediate benefits must be evaluated in comparison with any potential opportunities for improved ecosystem stability.

Grazing management approaches for tropical grasslands need to be enhanced. Critical considerations include the invasion of woody plants, the lack of palatability and limited productivity and nutritive value of the stable plant community on many infertile tropical grasslands, the lack of information on population dynamics of many communities, and the lack of predictability of rainfall in most tropical grasslands. Certainly the importance of infrequent combinations of events, such as appropriate rain in one season for seed production of a desirable plant followed by favorable conditions for germination and establishment in a subsequent season, must be considered in grasslands with erratic rainfall patterns. Also, especially in semiarid regions, the long-term nature of any improvements in vegetation in comparison with the potential for rapid deterioration (in such situations as excessive grazing pressure during extended drought) must be recognized. Such hazards to stability of these grasslands suggest that plans must be developed and implemented to adjust grazing pressure as drought conditions are recognized before excessive damage to the plant community has occurred. Reduction of herd size prior to the most adverse effects of severe drought, rather than initial short-term supplemental feeding of livestock, may be the least damaging alternative in many situations. Some basis for the required anticipation of continuing drought to trigger implementation of drought management strategies may be provided by further improvement of recent efforts to model regional climatological patterns.

Livestock needs must receive continuing consideration, with seasonal supplementation of minerals and protein often essential for economical livestock production. Effects of such supplements on the total grassland-based livestock production system must be considered. Also the extreme seasonality of herbage production, often further complicated by erratic rainfall, and the rapid decrease in forage quality with plant maturity are tremendous constraints on the productivity of livestock in tropical grasslands. These constraints often result in low levels of both reproduction of mature animals and the growth and maturity of young animals. Substantially lower livestock production from tropical grasslands than that typical of temperate livestock production systems is currently the case. A small portion of the tropical grasslands consists of planted pastures. Some of these pastures, especially in more humid areas, are intensively managed with livestock production levels similar to those of the temperate grasslands.

Rather short-term economic conditions and/or livestock needs rather than continuing productivity or stability of the grassland are sometimes primary considerations in management of some tropical grasslands. Social and political factors limit the options available for use and management of tropical grasslands in other situations. Nonetheless, productive, stable tropical grasslands and associated livestock enterprises are currently maintained across the range of tropical grassland environments, especially where rather conservative grazing pressures are maintained to provide surplus herbage as a buffer during droughts.

VIII. Current Environmental Concerns

Public awareness of potential and present global environmental problems has recently increased the sensitivity of governments and industry to some of the long-term consequences of decisions regarding tropical grasslands. Desertification in arid and semiarid regions can be accelerated, especially during extended drought conditions over several years, by developments intended to improve commercial production or even living conditions for people under marginal conditions. Drilling of water wells to allow greater utilization of such grasslands has been suggested to allow degradation of these areas through overgrazing which might not otherwise have been possible due to lack of available water for livestock. Likewise, improvements in animal health, which are not accompanied by use or marketing of the increased animal numbers, can lead to herd increases in good years and subsequent excessive overgrazing in dry years. Introduction of such technology to new areas must be accompanied by continuing educational efforts to reduce the opportunity for undesirable consequences. Often the choice may be between the maintenance of a slight buffer of a few cows by people living under precarious subsistance conditions versus avoiding the possibility of continuing grassland deterioration if rain does not occur soon.

A continuing increase in human populations in semiarid grassland regions during recent years is increasing pressure on productivity and sustainability of these systems. Livestock numbers have been increased in some extremely fragile environments to sustain the increased human populations. The extreme variability in herbage production from year to year and the recurring nature of droughts suggest that alternatives and strategies beyond those available to individual pastoralists must be provided for stability of these environments.

At the other end of the moisture extreme, grasslands are maintained on lands capable of producing forest, thus contributing to deforestation or at least preventing or slowing reforestation. Grasslands typically are relegated to lands which are unsuited for other higher value uses largely due to various adverse soil conditions. Deforestation is generally for purposes other than grassland development, although once depleted of nutrients and perhaps even topsoil, secondary grasslands often develop. These may develop or persist primarily through the assistance of man utilizing livestock and burning. Again, economic decisions, sometimes at the subsistence level, may require contrast of immediate benefits with potential future consequences.

Additional environmental modifications involving the natural grasslands, which are generally less dramatic than desertification and deforestation include decreases in food and habitat available for wildlife and the change from natural to managed environments as livestock production increases in intensity. Such changes are generally necessary for increases in livestock productivity and sometimes for economic survival of livestock production enterprises. Appropriate consideration of the additional ecological, recreational, and esthetic values of tropical grasslands will be provided as economic values are placed on these alternative uses and values.

A continuing dilemma in management of most tropical grasslands contrasts the need for high stocking rates to efficiently harvest herbage production during wet seasons of the year and during favorable years, while the herbage is of high nutritive value, with the need to maintain (or at least avoid starvation of) livestock during the dry season and sometimes even for periods of years of drought. While stocking rates may currently be marginally higher than appropriate in some areas, decreased livestock productivity rather than excessive environmental degradation is often the recurring effect of such marginally high stocking rates. However, throughout the tropical rangeland areas where recurring drought is a factor, stocking rates are typically high enough to make livestock systems and their grassland resource quite vulnerable to degradation from extended drought. This hazard suggests that alternative plans for grazing livestock during drought are imperative and must be developed on both individual and regional levels.

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Tropical Pasture Development

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Glossary

Forage Portions of herbaceous and woody plants, other than harvested grain, which can be consumed by ungulates

Forage quality Value of particular forage for maintenance and productivity of specific classes of ungulates encompassing the concentration and availability of the various nutrients, potential intake of the forage, and any associated antiquality factors

Germplasm Genetic resources including both naturally occurring species and ecotypes and unique genotypes derived from genetic manipulation

Grazing pressure In general terms, the impact of grazing on plants or plant communities; in a more specific sense, the number of animal units per amount of available forage at a specific time

Herbage Above-ground biomass of herbaceous plants

Legume Member of the plant family Leguminosae (Fabaceae)

Monoculture Cultivation or production of a single crop or plant species on an area to the exclusion of other potential crops or species

Sowing Process of planting seed

Vegetative propagation Increase (spread or establishment) of plants by means other than seed, typically involving either rhizomes or stolons

Tropical pasture development is the deliberate alteration of existing plant communities involving the introduction of selected tropical forage plants to enhance the value of a site primarily for the production of forage for grazing animals. Fencing for control of grazing livestock and development of water sources are also integral aspects of pasture development.

I. Purpose and Scope

The purpose of pasture development in most instances is to increase both productivity and profit potential of domestic livestock enterprises. On a broader regional or national scale, the purpose of tropical pasture development is often to enhance the economy through increased productivity, to increase availability of milk or meat to improve human diets, and/or to restructure degraded landscapes into productive, stable environments.

Agronomic requirements for establishment and management of tropical forage plants involve similar principles over the range of their area of adaptation; thus, tropical pasture development extends to the subtropical and semi-arid environments where tropical pasture species are adapted. Pasture development typically occurs on sites which are not suitable for more intensive uses such as crop production. Social and political structures which do not provide opportunities for individual land managers to benefit from grassland improvement or even maintenance of existing grasslands are often limitations to tropical pasture development and contributing factors to the deterioration of grasslands. [*See* RANGELAND GRASS IMPROVEMENT; RANGELAND GRAZING; TROPICAL GRASSLANDS.]

There are substantial contrasts between approaches appropriate for development of tropical pastures in some regions and those typically used for temperate pastures. While the high degree of success with temperate pasture development suggests that it could provide a model for the less extensively studied tropical counterpart, several factors must be considered. Temperate pasture development has succeeded through the selection and breeding of a very small number of grass and legume species which are primarily suited to humid environments. While development of cultivars for specific environments has been a critical aspect of this success, continuing modification of the environment to fit the plants is also an integral part of temperate pasture technology. This modification often includes the annual or more frequent application of fertilizers, drainage of wet areas, irrigation of dry areas, and regular application of herbicides and sometimes even other pesticides. Also, complete reestablishment of the pasture system after a few years is sometimes necessary. While such intensive systems may be appropriate in some situations, tropical pastures often must be inexpensive to establish, be even less expensive to maintain, and be sustainable for decades rather than just years. Costs of failures are often measured in ecological terms rather than simply in economic terms.

II. Climatic and Edaphic Considerations

Tropical climates which provide uniform availability of adequate amounts of moisture can support continuous growth of the most vigorously growing tropical forage plants. Such climates provide opportunity for the highest levels of herbage production. Such moist tropical climates also are generally suitable for the production of many other crops including high-value tree crops, food crops for human consumption, and forestry. Thus, despite the tremendous potential productivity of tropical grass pastures in moist climates, pasture development is often not the highest use of these resources. Most of the land in moist climates which is available for the development of tropical pastures has limited value for many other uses due to constraints such as steep slopes, poor drainage, poor soil structure, shallow or stony soils, low fertility, or other soil chemical imbalances. Limitations such as inadequate drainage and low fertility typically restrict the range of suitable forage plant species and their potential productivity but not the use of these lands for pasture development.

The characteristic seasonal distribution of rainfall in the zones between equatorial regions and the subtropics greatly affects the potential agricultural uses of land. Where rain occurs over a long enough period to produce crops, such crop production typically receives priority over pasture development. Where soil fertility is rapidly depleted by crop production, pasture may be a secondary use or pastures may comprise long-term components in crop rotation systems. Where other edaphic conditions limit production of crops, they also are often limitations to the establishment of tropical pastures. However, once established, pastures of adapted species may be quite productive and sustainable under appropriate management even on steep slopes, wet sites, soils of poor tilth, etc.

As total amount of annual rainfall or length of the rainy season becomes inadequate for crop production, pasture often becomes the potential use of highest value. However, rainfall in such environments is often unpredictable as well as low in annual amount. Even though pastures of selected species may have considerably higher herbage production potentials than the existing natural vegetation, establishment of introduced pasture plants involves high risk of stand failure in the more adverse environments. When the existing vegetation is disturbed to provide a seedbed for enhanced opportunity of establishment by sown species, potential for soil erosion and invasion of undesirable plants as well as economic loss are greatly increased in erratic-rainfall environments.

Selection of forage plants adapted to, or tolerant of, adverse soil factors is the most promising approach for overcoming such limitations to tropical pasture development. Although some advances have been made toward development of cultivars suited to specific adversities, a wealth of diverse tropical germplasm is available for further progress. Intensive pasture management involving substantial inputs to overcome soil limitations is not necessarily an inappropriate approach to tropical pasture development. Especially in humid environments, such an approach can provide highly productive livestock systems. However, over extensive areas of the tropics and subtropics, such systems are difficult to sustain within current restraints. [*See* FORAGES.]

III. Tropical Grasses

Grass cultivars currently available for tropical pasture development possess some rather distinctive characteristics, which affect both their practical use and potential improvement. Many of the productive, aggressive tropical grass cultivars do not produce seed or at least do not produce seed in sufficient quantities for establishment of pastures by sowing seed. Extensive pasture areas have been established from stem cuttings of tropical grass cultivars of the genera *Cynodon*, *Digitaria*, and *Hemarthria*. Such vegetative propagation of these stoloniferous grasses typically provides more aggressive, competitive stand establishment than that obtained with sowing of seed of seed-propagated species. Vegetative propagation maintains genetic integrity of cultivars, but it also can result in lack of genetic variability so that extensive areas planted to monocultures of one superior cultivar are vulnerable to rapid, extensive damage from insects and diseases. Either low-cost labor or high levels of mechanization have proven to provide particularly suitable conditions for successful planting of extensive areas by vegetative means.

While limited seed production has precluded sowing of seed of some species of the genera mentioned above, sufficient seed production typically occurs to allow genetic improvement of germplasm through plant breeding approaches. Additional tropical grasses which are excellent seed producers have provided distinct challenges to the use of plant breeding for genetic improvement. Several tropical grass species which have been widely used in pasture improvement are capable of apomictic reproduction. This method of reproduction involves structures commonly utilized in sexual reproduction but without actual fusion of male and female gametes. Thus, attempts at crossing plants, which reproduce apomictically, produce uniform progeny identical to the female parent. Apomictic seed production is more common in the tribes Paniceae and Andropogoneae than in other grass tribes. Identification of sexually reproducing plants of some apomictic species has allowed genetic improvement to be made by utilizing sexually reproducing female parents and selection of superior apomictic progeny to secure the genetic advances into new uniform cultivars. Exclusive planting of a superior individual apomictic cultivar, as with vegetatively propagated cultivars, can produce extensive grasslands which do not possess the genetic diversity to adjust readily to plant pests. The various mechanisms of apomixis (apospory is typical of species of *Panicum*, *Paspalum*, and *Cenchrus* of the subfamily Panicoideae, while diplospory is the form identified in the genus *Eragrostis* of the subfamily Eragrostoideae) and extent of obligate and facultative expression of the trait complicate the process of tropical grass improvement. In some cases, considerable basic cytogenetic investigation is required for advancement of genetic improvement and development of improved cultivars of apomictic species.

On the other hand, tropical pasture grasses which reproduce sexually and produce adequate seed quantities for sowing pastures are not without disadvantages. Even perennial grasses, especially those which do not form dense canopies or spread aggressively by rhizomes or stolons, typically are continually being renewed by development of new seedlings within the stand. Highly heterogeneous cultivars and especially those composed of composited germplasm can experience change in pasture composition over a period of years in response to natural selection pressure or grazing conditions. Genotypes which differ in palatability can be composited into a single cultivar which may readily be transformed into a sward dominated by the least palatable genotype within a few years of grazing.

Grasses for tropical pasture development should be both productive and sustainable. The large number of diverse and often adverse environments represented and the requirement for plant persistence with minimal inputs have resulted in the consideration of a very large number of plant species for potential use in tropical pasture development. Tropical grass cultivars are largely from the subfamily Panicoideae, tribe Paniceae. Additional cultivars have also been developed from individual genera of the subfamily Eragrostoideae, tribe Chlorideae. The aggressive characteristics of some weedy and invading species have contributed to development of cultivars of these species able to meet the need for rapid establishment. High levels of herbage production are also characteristic of these aggressive grasses. As with temperate grass cultivars, the aggressive tropical grass cultivars are often dependent upon high levels of soil fertility for productivity and stand survival. Thus, declining productivity and eventual stand loss have been problems with tropical pasture development where regular fertilization has not been a viable management option.

Increased emphasis on sustainability indicates that species of the grass subfamily Panicoideae, tribe Andropogoneae should receive further attention. While use of *Andropogon gayanus* on infertile South American sites has apparently been successful, efforts with species of *Schizachyrium* and *Tripsacum* have reflected the characteristic limitations of this tribe in seed production and quality. Cultivars of the genus *Hemarthria* possess herbage nitrogen concentrations low enough to require protein supplementation for optimal performance of some classes of livestock even during the growing season. This is characteristic of the nitrogen use efficiency of the tribe. Thus, present Paniceae and Chlorideae cultivars with aggressive establishment and herbage production qualities and limitations in sustainability contrast with the potentially more sustainable tribe Andropogoneae which is typified by limitations in establishment and forage quality.

The major tropical grass cultivars are primarily of African genera, including *Brachiaria*, *Cenchrus*, *Chloris*, *Cynodon*, *Digitaria*, *Melinis*, *Panicum*, *Pennisetum*, and *Setaria*. In general, these grasses are tolerant of grazing, as would be expected from development under the most intense grazing conditions of any tropical environment. They are also generally aggressive and productive, partially due to recent intentional selection for these qualities, but perhaps also due to development under marginal conditions where recurring forest disturbance and nutrient release provided selection pressure for such aggressive colonization of new areas. The genus *Paspalum*, which has contributed primarily in the subtropics and warm temperate regions, is the most widely used tropical American grass genus. Even cultivars adapted to infertile South American sites have primarily been developed from African species such as *Andropogon gayanus* and *Hemarthria altissima*.

IV. Tropical Legumes

A potential solution to the dilemma of maintaining adequate nitrogen levels to sustain the Paniceae and Chlorideae grass cultivars is through biological nitrogen fixation of associated legumes, which has received considerable attention over the past 30 years. Tropical legumes are widespread in the American tropics, where soil fertility in many situations has been low and provided a competitive advantage to the legumes. Even though of tropical origin and adaptation, tropical legumes utilize the C-3 photosynthetic pathway typical of temperate grasses and legumes. Thus, in warm, fertile, high-sunlight tropical environments, the tropical legumes are at a competitive disadvantage to the tropical grasses with the more efficient and productive C-4 photosynthetic pathway. Various characteristics of individual tropical legumes, such as climbing growth habit, adaptation to shade, and an extended period of growth after growth of grasses has been slowed at initiation of the dry season, help to offset this growth advantage of the grasses under pasture conditions. Early efforts to select legumes primarily for establishment ability and high yields resulted in development of some cultivars that require specialized management for sustained stands. Recent tropical legume cultivars with increased tolerance of grazing include some that are less palatable than the grasses and others with morphological characteristics such as woody stems or prostrate growth under grazing. However, combinations of grasses and legumes for sustainable, productive, low-input tropical pastures have not been developed for most situations.

The great diversity of tropical legumes possessing desirable characteristics for pasture use indicates that advancements, though amazingly elusive in the past, should still be expected. In environments with distinctly unfavorable conditions occurring on a seasonal basis, efforts to develop legume cultivars should capitalize on the natural plant strategies for avoiding such conditions. Thus, the annual legumes should receive greater attention in drastic environments where perennials do not reliably survive an adverse season. Annual legumes also have potential in drier environments where grass growth is not so dense and competitive that seedlings are adversely affected by the grass stand during establishment. Pastures based on annual legumes are particularly vulnerable to erratic rainfall early in the growing season and excessive grazing late in the season when seed is produced. This vulnerability can be partially overcome by hard-seeded legumes which can provide supplies of seed for several years from a single good seed-production year.

As rainfall increases to support a more dense grass stand and the dry season is mild enough to allow survival of perennial legumes, the advantages of annual legumes are greatly diminished compared with their disadvantages. However, the importance of seed production, hard-seededness, and establishment of new legume seedlings is not diminished greatly. Many of the herbaceous perennial legumes are rather short lived. Although complete stand establishment is not required each year, stand stability does require a continuous process of new seedling development to offset plant mortality of most species. While hard-seededness is an advantage to legumes in established pastures, it is often a trait which must be overcome, at least partially, for acceptable establishment with sowing of new pastures. Seed scarification is a requirement for acceptable germination of some, though not all, tropical legumes. Additional similar characteristics of seed-propagated legumes (and grasses) which are advantages for existing stands and disadvantages for plant domestication are indeterminate flowering and seed shattering. For harvest of seed crops, uniform development and seed retention are highly beneficial to harvest of high proportions of the seed produced. Thus, the degree of domestication desired with forage plants often is a compromise between the natural advantages of existing traits and the requirements for economical seed production and initial establishment of new pastures.

The woody legumes, such as the genera *Acacia*, *Albizia*, *Calliandra*, *Desmanthus*, *Gliricidia*, *Leucaena*, and *Sesbania*, have recently been recognized as potentially possessing ecological advantages for use in tropical environments which are capable of supporting woodland plant communities. These legumes may provide sustainable systems where their deep roots utilize moisture supplies that would otherwise favor invasion of pastures by other woody plants. They could also sustain the cycling of nutrients from greater depth and store nutrients more effectively than either the grasses or the herbaceous legumes. While much of the attention has been focused on agroforestry and associated production of food crops, many of the woody legumes have potential value as pasture plants or at least as fodder crops. In addition to development of sufficiently aggressive and adapted genotypes for successful use, particular caution must be used not to introduce excessively competitive types since brush problems in many grasslands are presented by shrub legume species.

Most of the genera providing cultivars of the herbaceous tropical legumes such as *Aeschynomene*, *Centrosema*, *Desmodium*, *Macroptilium*, and *Stylosanthes* are of American origin. However, Asia and Africa also have been sources of important tropical legumes, including the genera *Alysicarpus*, *Neonotonia*, and *Vigna*. Tropical legume cultivars of American origin are primarily from low-fertility, leached soils with limited grazing pressure. Rather recent cultivars of *Desmodium* from Asian germplasm and *Vigna* from African origin indicate that despite large numbers of species and considerable diversity in American legumes, grazing tolerance may be more widely available from sources with a history of grazing pressure. Thus, current limitations to persistence of tropical legumes may be overcome by use of herbaceous legumes with morphological adaptations which allow them to partially escape excessive defoliation or by use of woody legumes which produce at least some foliage beyond grazing or browsing height. Both these and other means of escaping and/or tolerating the effects of grazing defoliation will likely be necessary to provide suitable legumes for the many diverse tropical environments.

Unlike the tropical grasses which generally are adapted over rather broad areas encompassing ranges in moisture and soil conditions, the tropical legumes respond to very subtle environmental differences. Often only slight changes in slope, soil texture, fertility, moisture, and especially plant competition make the difference between aggressive growth and complete loss of tropical legume stands. With a few individual species, such as those of the genus *Lotononis*, the requirement for a specific rhizobial inoculant can be a primary factor. However, for most tropical legumes, such rhizobial specificity is not a factor as it typically is with temperate legumes. Thus, narrow ranges of adaptation of tropical forage legumes may be a characteristic which necessitates the development of cultivars of a large number of different species and perhaps even the use of mixtures of legume species.

V. Germplasm Development

While recognition of the potential of tree and shrub legumes is perhaps the most recent major advance in tropical pasture development, the use of improved tropical forages in general is more recent than that of temperate forages and much more recent than efforts to improve the major food crops. Thus, experience with other crops indicates that tremendous potential exists for genetic improvement of tropical forage plants. However, the asset of tremendous quantities of highly diverse germplasm, which provides the opportunity for rapid progress with genetic manipulation, is also the reason not to immediately and extensively pursue the genetic manipulation of individual germplasm for numerous specific improvements. While in a few situations this may be the appropriate approach, in most tropical environments the available germplasm with potential value has not been sufficiently evaluated to even identify the most suited species. This is particularly the case for the tropical legumes. [*See* PLANT GENETIC RESOURCES; PLANT GENETIC RESOURCE CONSERVATION AND UTILIZATION.]

Timely efforts to obtain and store extensive collections of germplasm of tropical forage plants have been made during the past 15 years. Australian pasture scientists were leaders in both the early development of tropical forage technology and the recent collection and storage of existing germplasm. They were joined on a large scale in germplasm collection and storage by the system of international agricultural research centers with leadership from Centro Internacional de Agricultura Tropical (CIAT) in Cali, Colombia. This location especially facilitated the collection of tropical legumes which are more widespread and diverse in the American tropics than anywhere else. This accumulation of germplasm has far outpaced efforts to characterize the germplasm and determine the potential of various available genotypes in various environments. Considerable advancement in tropical forage development will likely result from identification and use of the superior germplasm currently available.

VI. Economic and Ecological Constraints

Costs, potential returns, and risk of failure require a combined evaluation of aspects of economics and ecology of tropical pasture development. Costs and risks of site deterioration increase with the degree of modification of the existing vegetation. Simply introducing seed of a desired species into existing vegetation, referred to in Australia as augmenting native pasture, minimizes cost with perhaps a rather high risk of failure. In environments with predictable rainfall patterns, risk of establishment failure can often be progressively reduced with increasing degrees of seedbed preparation at increasing cost. However, in environments with erratic rainfall, risk of stand failure may not be reduced enough to justify the increased cost and risk of site deterioration accompanying intensive seedbed preparation.

While sustainability of tropical pastures is critical, inputs to enhance stand life or even replace degraded pastures may not be unreasonable for high value uses such as milk production and fattening of slaughter animals on sites not subjected to excessive degradation from periodic cultivation. Such high return uses of tropical pastures, and even less intensive uses in particular economic circumstances, may result in advantages for nitrogen fertilization of grass pastures over grass–legume mixtures. The response of grass to nitrogen fertilization in humid and subhumid environments is often more predictable and productive than dependence on legumes for nitrogen. As intensity of management and production potential decrease, the advantages of legume technology over nitrogen fertilizer generally increase.

Invasion of planted pastures by other plants is an essentially universal phenomenon. Pasture deterioration of some extent results. Intensively managed pastures may be routinely subjected to treatment with selective herbicides or mechanical defoliation to control invading broadleaf weeds or woody species. Hand labor and fire are also frequently used options for control of woody plants. Fewer options are available for control of weedy grasses in introduced grass pastures. Options available for control of broadleaf weeds and woody plants are reduced when legumes are components of the pasture, since many herbicides which control these weeds also damage the pasture legumes. Since the pasture legumes are differentially affected by fire, knowledge of the response of a particular legume cultivar to fire is a critical factor in deciding among options for controlling woody plants. In the long term, development of pasture cultivars better suited to specific environments, which are both productive and capable of competing with invading species, provide the preferred option. Appropriate extent of herbage utilization and use of key periods of deferment from grazing may also increase the competitive ability of introduced pasture plants.

VII. Animal Needs versus Available Herbage

Early during the season of active plant growth, the herbage available in tropical pastures is generally at its highest nutritive value for ruminant livestock. Young leaves are generally the plant parts highest in protein and digestibility. As herbage accumulates during the growing season, the proportion of older plant tissue increases while both digestibility and protein concentration decrease. Morphological development also produces increasing proportions of stem, which is typically lower in forage quality than are leaves. In addition to the biological fixation of atmospheric nitrogen into forms available for plant use, pasture legumes are typically higher in protein than the grass available for grazing through most of the year. Thus, selected pasture legumes provide potential to enhance quality of diets of grazing animals, often increasing intake of the lower quality grass and further enhancing animal performance even beyond that due to the nutrients contained in the legume herbage itself.

As the characteristic dry season in the tropics and cool temperatures or frosts in the subtropics decrease or even terminate plant growth, the nutritional value of the remaining herbage often deteriorates rapidly. A large portion of the gains made by grazing animals during the growing season are lost during the dry season in many tropical environments. Selection of forage plants for ability to retain green leaves, a characteristic of some deep-rooted legumes, or simply to retain higher forage quality into the dry season provides potential for improvement of animal production. Protection of such herbage from utilization until the appropriate season becomes a management consideration. This concept can be extended to simply reserving areas of existing grassland for dry-season use so that minimal supplementation and available roughage may prevent excessive weight losses by grazing livestock. Despite the higher forage quality of many tropical legumes, on infertile tropical soils some legumes are not heavily utilized while the grasses are actively growing. Such legumes provide naturally deferred herbage for dry-season use.

Grazing management strategies can be developed beyond simple deferment of grazing for later use to complex grazing systems which address additional concerns. Rapid rotation systems have been promoted for enhancement of pasture utilization and increases in carrying capacity. Increased herbage utilization in such systems can sometimes be attained without decreases in individual animal performance, as typically occurs on continuously grazed grasslands, because cattle are moved through the rotation rapidly so that regrowth of essentially all pasture plants is young and nutritious when grazed and cattle remain on a pasture only for a short time. Intensive grazing systems can also be developed primarily from the perspective of providing near maximum individual animal performance, especially during the growing season. These systems differ from the rapid rotation systems just mentioned primarily in extent of grazing pressure. These latter systems often utilize short grazing periods and light stocking rates to maintain relatively high availability of high-quality forage. In some pasture types, cattle utilize primarily the upper leaf canopy. Periods between grazing cycles are also short to allow grazing of regrowth while forage quality is still high. Livestock responses to such systems are greatest with young growing animals or in milk production systems. However, production responses from such intensive systems are primarily restricted to the growing season; thus, these systems do not contribute directly during periods of greatest nutrient deficit (such as extended dry seasons).

The use of stored herbage such as hay and silage for dry-season feeding has not been widely used in the tropics. As intensification of tropical livestock production systems increases, use of such technologies to provide quality dry-season feed will perhaps increase. Potential production of selected tropical grasses in favorable environments with such systems is tremendous. Where grassland based livestock systems are integrated with crop production enterprises, considerable dry-season feed for livestock can be derived from crop residues and even production of annual herbage crops for dry-season grazing or feeding. By-products of the processing of tropical crops provide another dry-season feed source for grassland livestock production. The nutritive value and methods of most efficient utilization of many of these tropical crop by-products have not been thoroughly evaluated, even though the available by-products are commonly used to some extent.

VIII. Additional Pasture Management Considerations

Grazing systems may be developed around the needs of the pasture plants rather than, or in addition to, the consideration of livestock needs. In some situations, requirements of plants for maintenance and productivity are not adequately addressed by prevailing grazing management. Highly palatable plants, especially when grown in mixed stands with less palatable species, may require periods of deferment from grazing for survival. These deferment periods may be satisfied simply by rotational grazing providing regular recurring opportunities for regrowth. In other instances, the season of deferment from grazing may be critical. Appropriate seasons of deferment from grazing can allow heavily grazed plants to regain vigor immediately prior to stress periods. Plants may respond to such deferment by storage of energy for subsequent use, by increased seed production, or through immediate increase in plant size and even vegetative propagation. Annual legumes, as components of perennial grass pastures, may require reduced grazing pressure during the season of seed production, while benefiting from heavier utilization of the associated grass during the period of legume establishment.

Nonstructural carbohydrates and other labile plant compounds can be mobilized and used in plant growth. These components, primarily total nonstructural carbohydrates, have been extensively used to evaluate effects of defoliation on vigor and regrowth potential of temperate forage plants. The high rates of photosynthesis of tropical grasses and less than complete leaf removal by grazing defoliation suggest that stored energy may seldom be a controlling factor in the grazing management of tropical grasses. However, even with the tropical grasses, initiation of new leaves following complete defoliation is dependent upon existing energy sources. Thus, plant vigor at onset of the dry season or at the first frost in the subtropics can be critical to survival of some plants. This becomes even more critical in erratic environments where intermittent light rain or warm temperatures permit repeated leaf initiation with subsequent defoliation. Thus, while stored energy may not be a factor in growth of most tropical forage plants during the season of active growth, energy available for leaf initiation following complete defoliation by drought or frost can be critical in some situations.

IX. Global and Societal Concerns

The growing problem of desertification and its effects on pastoral societies and beyond suggest that technological developments to restore stable and productive vegetation should be a priority in arid and semi-arid grassland research. Identification of sites with greatest potential for revegetation could provide enhanced opportunities for successful small-scale plantings. Innovative means of site enhancement for plant establishment and selection of plants with superior establishment ability for use as pioneer species may be critical for greater success. Refinement of the prediction of global weather patterns and enhanced understanding of the processes of natural revegetation during favorable years may allow reseeding at times with greatest opportunity for success. Such intensive practices as site modification and planting may be used on a limited scale along with strategies to enhance opportunity for further spread and colonization on these extensive, minimally productive grasslands.

While tropical pastures are generally less intensively managed than most other agricultural lands (that is, they typically receive lower input levels), potential effects of chemical fertilizers and pesticides on the total ecosystem must be considered. Less stringent or even complete lack of government regulations regarding the use of hazardous chemicals in many tropical locations necessitates a greater individual responsibility in use of such materials.

Seedbed preparation with subsequent stand failure provides opportunity for soil erosion and site deterioration. Inappropriate choice of pasture species may result in short-term stand life followed by site deterioration. Relatively low-cost land in many tropical locations can be a considerable incentive to investment and development despite high risk. Increased availability of information regarding appropriate levels of development for specific sites, suitable species for sustainable use, and risks involved could reduce the failures and resulting environmental damage due to inappropriate approaches to tropical pasture development.

Concerns exist in some affluent, highly developed societies that livestock may be detrimental to the environment. Livestock production does typically result in changes in ecosystems. Often increasing improvements for livestock production result in decreasing suitability for many wildlife species. Additional concerns include the release of carbon into the atmosphere, from storage in high quantities in forest biomass, as humid pasture development occurs. Recent information indicates that carbon storage in forest, although greater than in grassland, may not be as much greater as previously thought, since grassland has been found to have a much higher proportion of below-ground biomass than forest typically has. Agriculturalists must be more aware of opportunities to minimize adverse effects of pasture development on other values and uses of land. However, the immediate needs of local people must be recognized, and appropriate compensation for alternative uses of existing and potential pasturelands may serve all interests. Continuing increases in population require increases in food production. Since tropical grasslands are the least intensively managed terrestrial food production resource, they may provide the most responsive opportunity for increased food production during the next decade or two. Thus, the tremendous opportunity for increased production of livestock to meet human nutritional needs through pasture development in many tropical regions must be carefully evaluated with due consideration to the environmental and economic costs and risks.

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Tropical Rain Forests: Hydrology and Climate

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Glossary

Albedo Ratio of reflected solar radiation to the incoming solar radiation, both integrated over all wavelengths in solar radiation

Atmospheric humidity deficit Difference between the concentration of water vapor in the air at air temperature, which is saturated with water vapor, and the actual concentration of water vapor in the atmosphere

Conductance Reciprocal of resistance

GCM General circulation model, a numerical computer model which predicts the state and movement of the atmosphere over the entire globe

Interception loss Rainfall which is intercepted by a plant canopy and evaporated directly back into the atmosphere without reaching the soil during rainfall and shortly after

Runoff Transport of water from a catchment

Stomata Small openings in the leaves of plants through which water vapor escapes and carbon dioxide is taken up

Surface, or bulk stomatal, resistance Total effect of all the individual stomatal resistances, considered to occur at one level in the canopy

Transpiration Process by which water, which is taken up by plants through the roots, is evaporated into the atmosphere through the stomatal openings on their leaves

Tropical rain forest is the climax vegetation of the humid tropics. This forest is at least partly evergreen and is typified by a dense, diverse canopy which is continuous from the ground surface to 30 m or higher and which completely covers the ground (Fig. 1). The forest grows in areas with an average annual rainfall greater than about 1500 mm and where the annual dry season is short or nonexistent. Although forests in these areas of the tropics are commonly called rain forest, moist tropical forest is a more appropriate scientific description. Annual evaporation is between 1000 and 1500 mm and comprises a transpiration component and evaporation of rainfall intercepted by the canopy. The atmospheric moisture generated by these processes interacts with the weather systems to maintain the humid, tropical climate.

I. The Hydrological Cycle

Most of the rain falling on the forest canopy is intercepted by the leaves (Fig. 2), the remainder falls through gaps directly to the ground. When the canopy is saturated, most of the water then drips to the ground to replenish the soil moisture store. Similarly, some water reaches the ground by flowing down the outside of the branches and trunks of the trees. Some of the water intercepted by the canopy evaporates directly back to the atmosphere; water which reaches the soil may be returned later through the roots and leaves (transpiration) or may percolate down to deeper layers, eventually contributing via throughflow to the river discharge. In undisturbed forest, Hortonian overland flow from the surface is generally not observed.

Clouds are formed by moist air rising to a level where the air temperature is sufficiently cold to cause the water vapor to condense. Rain then forms when the cloud droplets coalesce. The actual rainfall depends on the amount of precipitable moisture and the speed at which the rising air reaches the condensation

FIGURE 1 Photograph of tropical rain forest in Reserva Jaru, J Paraná, Rondonia, Amazonia (Photo by J. H. C. Gash.).

level. The amount of precipitable moisture is determined by both the evaporation from the surface and the large scale weather patterns, importing moisture into a region. For instance, for the Amazon basin it is estimated that 50 to 60% of the precipitation originates from water which was evaporated by the forest. The remaining 40 to 50% of the moisture is transported inland from the ocean by the Northern Hemisphere trade winds (Fig. 3). The rain forests in the Amazon thus play an essential role in maintaining the wet, humid climate on which they are dependent. [*See* METEOROLOGY.]

II. Interception of Rainfall

The canopy of a tropical forest has a large leaf area which intercepts most of the rainfall falling on to it. The aerodynamically rough forest surface generates a highly turbulent air flow which provides an efficient mechanism for transferring water vapor from the wet leaves to the atmosphere; this results in high evaporation rates during and after rainfall. Estimates of this interception loss are usually obtained by measuring the rain reaching the ground surface (throughfall) with a set of rainfall gauges randomly placed beneath the canopy. This presents a measurement problem in rain forest where the interception loss is a small difference between two large numbers: rainfall and throughfall. The problem is exacerbated by the heterogeneity of the forest canopy which gives great spatial variability in throughfall. As a result there have been few reliable studies of interception loss from tropical forest, but those that there have been show that some 10 to 15% of the rainfall is evaporated in this way, i.e., for a rainfall of 2000 mm, 200 to 300 mm are evaporated directly, without reaching the soil. In temperate forest interception losses of 30% are more common, but storms in the tropics are generally of high intensity and short duration, giving little time for evaporation during storms. In addition the tropical forest canopy appears to shed water easily, many species having shiny leaves with drip points. A saturated canopy holds the equivalent of only about 0.7 mm of rainfall, which is evaporated at the end of a storm. In contrast to forest, agricultural crops and pasture are less aerodynamically rough, have lower evaporation rates during storms, and consequently have low interception losses. One of the immediate effects of deforestation is to remove this component from the water

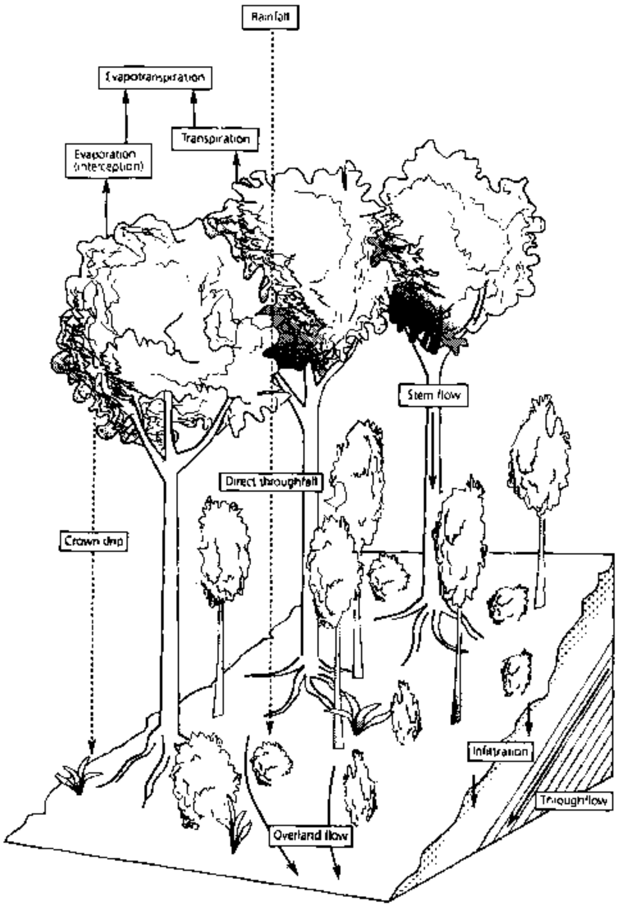

FIGURE 2 The hydrological cycle in a tropical rain forest. [Redrawn with permission from Bruijnzeel, L. A. (1990). "Hydrology of Moist Tropical Forests and Effects of Conversion: A State of Knowledge Review." Unesco, Paris and Free University Amsterdam.]

balance. This puts more water in the soil, but less water into the atmosphere. [*See* MICROCLIMATE.]

III. Transpiration

Transpiration is the process whereby water is taken up from the soil by the root system, transported through the trunk and evaporated through the stomata in the leaves. A typical value for lowland tropical forest is 1000 mm per year, while transpiration from montane forest is usually lower, but more variable. Transpiration can be estimated by micrometeorological techniques which measure water vapor as it moves through the turbulent atmospheric boundary layer above the forest. These techniques give measurements at a time scale of an hour or less which is useful for interpreting the response of the vegetation to environmental controls. Longer term extrapolation of these results can be obtained by running a well-calibrated micrometeorological model for the required time scale. It is likely that this combination of physically based modeling and measurement provides a good estimate for the long-term water balance of tropical forest. When this technique was applied to a tropical rain forest in central Amazonia it gave an estimated 1020 mm per year being lost to the soil through transpiration. This can be compared with estimates of transpiration for a typical mid-latitude forest of around 300–350 mm per year. In the Amazon study 90% of the incoming radiant energy was used to evaporate about 50% of the precipitation back to the atmosphere.

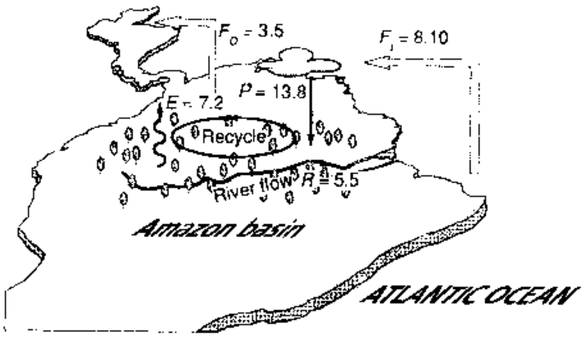

FIGURE 3 Schematic diagram of the water cycle in the Amazon basin. E is total evaporation (interception and transpiration), P is precipitation, F_i represents the amount of moisture entering the region, F_o represents the amount of moisture leaving the region, and R is the river flow of the Amazon into the Atlantic Ocean. The fluxes, denoted by arrows, are in units of 10^{12} m^3 year^{-1}. [Redrawn with permission of Kluwer Academic Publishers from Salati, E., and Nobre, C. A. (1991). Possible climatic impacts of tropical deforestation. *Clim. Change* 19, 177–196.]

IV. Runoff

Water, which reaches the soil layer and which is not used by the roots for transpiration, fills up the unsaturated moisture reservoir and percolates into the saturated zone, eventually leaving the forest as runoff, or riverflow. Due to the highly permeable soils, quick runoff (Hortonian overland flow) is hardly ever observed in undisturbed forest. Runoff generation in general and for tropical forest in particular is poorly understood. It is difficult to generalize individual catchment or water balance studies, as total runoff depends on the interplay between precipitation, soil hydraulic characteristics, and land morphology. For the Amazon basin as a whole it is estimated that 40% of the incoming precipitation leaves the basin as river discharge.

V. Micrometeorology of Tropical Rain Forest

Tropical rain forests are generally taller than comparable temperate forests and contain a far greater variety of tree species. Like temperate forest they are dense, extensive, and perennial. These aspects largely determine the interaction of the forest with the atmosphere.

The deep canopy and extensive leaf area of tropical rain forest are very efficient at capturing the incoming solar radiation. The leaf area of a forest canopy (Fig. 4), and the spectral properties, shape, size, and orientation of the leaves all affect the transmission and reflection of radiation through and from the canopy. The albedo (the proportion of the solar radiation which is reflected) of tropical rain forest is low—about 12% with sometimes a slight seasonal variation in the range 1–3%. In contrast, albedo values for tropical grass or tropical savannah are much higher, typically in the range 18–25%. Deforestation may result in a decrease of the amount of energy absorbed by the surface of up to 10%. The dense tropical rain forest canopy also results in only a small amount of radiation reaching the soil surface. Typically 2–5% of the radiation at the top of the canopy reaches the ground. In total, the combined effect of reflection and transmission results in a capture of about 85% of the incoming solar radiation by the forest canopy.

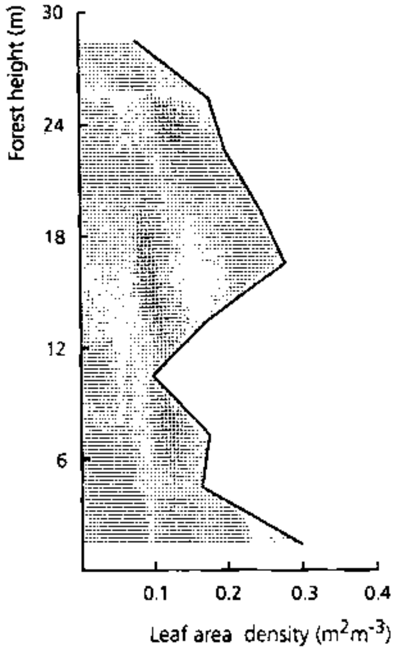

FIGURE 4 Distribution of leaf area density with height for a terra firme rain forest near Manaus, Amazonia. [Redrawn with permission from McWilliam *et al.* (1993). Leaf area index and above ground biomass of terra firme rain forest and adjacent clearing in Amazonia. *Funct. Ecol.* **7**, 312–317.]

The tropical forest, because of its height and amount of leaf area, exerts a relatively large drag on the air. This results in an environment just above the forest which is markedly more turbulent than that over grass. The air at the top of the canopy is therefore well mixed and the temperature of the vegetation at the top of the canopy is close to air temperature. Compared to the climate above short vegetation the climate above the forest changes relatively little during the day and has a lower maximum and higher minimum temperature. At the forest floor the air is significantly decoupled from above, with lower temperatures and higher humidities than those above. This gives high relative humidities, which combined with the low windspeeds give the forest its characteristic humid climate.

From the inside of the substomatal cavity, where the air is saturated with water vapor, the water escapes through the stomatal opening by molecular diffusion (Fig. 5). The diffusion through the stomatal opening presents a resistance—in analogy with Ohm's law—to water vapor transport which is called the stomatal resistance. The bulk integrated, stomatal resistance is the surface resistance of the forest. Values for maximum stomatal conductance (the reciprocal of resistance) of leaves vary by a factor seven, depending on species and position of the leaves in the

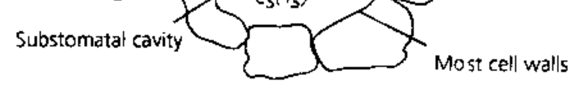

FIGURE 5 Schematic diagram of the molecular diffusion process of water through the stomatal aperture of dry leaves. Air inside the stomatal cavity is saturated (e_s (T_s) is saturated water vapor pressure at the temperature of the leaf and the water vapor diffuses through the stomatal opening to the atmosphere at water vapor pressure, e, against a stomatal resistance, r_s. [Redrawn with permission from Shuttleworth, W. J. (1988). Evaporation models in Hydrology. *In* "Land Surface Evaporation, Measurement and Parameterization" (T. J. Schmugge and J-C André, eds.). Springer-Verlag, New York.]

canopy. Tall, emergent trees have higher conductances than vegetation close to the ground. The diurnal pattern of the conductances also depends on the position of the leaf in the canopy. In the upper part of the canopy the daily maximum of conductance appears in the mid-morning, while the maximum becomes less pronounced deeper down in the canopy. At the forest floor the daily variation is virtually absent. Stomatal conductance usually increases with solar radiation and decreases with atmospheric humidity deficit. The fact that both the microclimate and the stomatal conductance vary within the canopy makes it difficult to use a single value to calculate evaporation. Adequate schemes, to integrate the effect of variation through the canopy, or multilayer evaporation models are necessary to calculate evaporation from a knowledge of stomatal conductance and weather.

The bulk stomatal or surface conductance of a rain forest can be obtained by inverting an evaporation equation such as the Penman–Monteith equation. Very few studies have had the data to do this. For the Amazon forest near Manaus a maximum value of conductance of 20.8 mm sec^{-1} was found from evaporation measurements obtained by the eddy correlation technique. Although the surface conductance shows a diurnal response to solar radiation, temperature, and humidity deficit, a clear response to soil moisture deficit has not yet been observed. This is a result of the deep roots being able to access a sufficiently large amount of soil water to continue transpiration through dry periods lasting up to at least several weeks. The common conception of rain forest trees having only a dense mat of roots close to the surface is not correct. They do have this—mainly for extracting nutrients—but they also have deep roots going at least 4–5 m into the soil enabling them to survive periods without rain.

VI. Effects of Deforestation

Understanding of the effects of deforestation on climate and hydrology can be obtained by analyzing observational records or by using numerical general circulation models (GCMs) of the atmosphere to predict the hydrological and climatological response to a hypothetical deforestation. Observation evidence for a relationship between rainfall and deforestation is scarce, due to the difficulties in obtaining reliable long-term records and the inherent variability of rainfall. There is a wealth of circumstantial evidence pointing to decreased rainfall as a result of deforestation, but, unfortunately, most of these studies do not meet the standard of scientific scrutiny. So-called paired catchment experiments in the humid tropics have shown that removal of forests may increase water yield by up to 800 mm per year. The highest increases are found 1 year after treatment (i.e., deforestation, logging). The response after the first year depends on the type of vegetation which establishes itself after deforestation and the extent of canopy closure. Evidence from controlled experiments also suggests that the largest increases in streamflow occur with the delayed flow component, which is most marked in the dry season. Evidence relating increased storm flow to logging practices is still controversial. This is partly caused by the fact that experimental basins do not necessarily reflect current logging practices.

GCMs attempt to model the three-dimensional patterns of rainfall, temperature, windspeed, and humidity of the earth's atmosphere. Using GCMs has the advantage that insights can be obtained in the interaction between the land surface and the atmosphere. The GCMs are based on physical laws, and sensitivity studies with these models allow identification of critical parameters in the surface energy and water budgets. Unfortunately, predictions with GCMs are limited by the resolution of the model grid, typically several hundreds of kilometers, the physical parameterizations used, and the specificiation of the input parameters. GCM experiments have improved the description of the forest atmosphere interaction by incorporation of more physically realistic models for the forest and the replacement vegetation.

To predict the impact of deforestation on climate and hydrology a control run is made with the surface parameterizations describing the existing tropical rain forest. In experiments the land surface parameters have been derived from measurements of evaporation, heat, and momentum flux obtained by micrometeorological techniques (Fig. 6). The "control" is then compared with observations so as to assess its capability to represent the current climate accurately. For the deforestation run, the forest is replaced by another vegetation (tropical grass or savannah) and the results compared with the "control" run.

In Fig. 7 the changes in rainfall and surface temperature are shown for an Amazon deforestation experiment. Most GCM experiments have predicted that deforestation leads to a reduction in rainfall. This reduction in rainfall is caused by both a reduction in evaporation and changes in atmospheric circulation pattern for the deforestation run. The reduction in

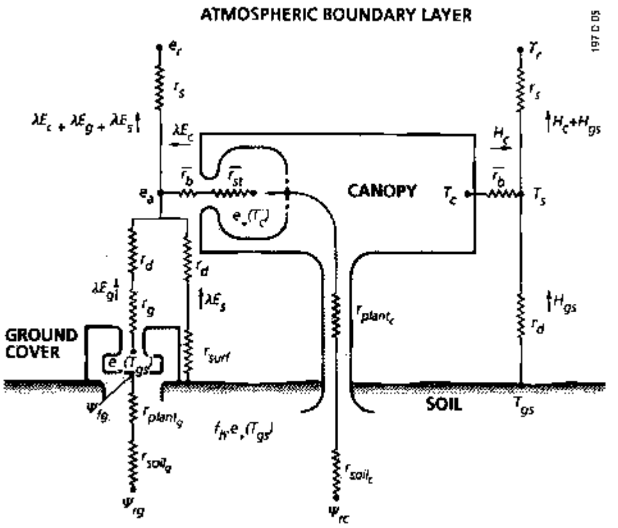

FIGURE 6 Schematic diagram of a land surface model (SiB) used in general circulation models. The transfer pathways for latent, λE, and sensible heat flux, H, are shown on the left and right side of the diagram, respectively. Fluxes are proportional to differences in temperature, T, water vapor pressure, e (e_* is saturated water vapor pressure), or water potential, ψ, divided by the appropriate resistance, r. The subscript r refers to reference height, a to canopy space, b to canopy element boundary layer, g to ground, l to leaf, d to air space between canopy and ground, c to canopy, s to soil, and st to stomatal. Resistances are shown in terms of an analogous electrical circuit. [Redrawn with permission of the American Meteorological Society from Sellers, P. J., Mintz, Y., Sud, Y. C., and Dalcher, A. (1986). A simple biosphere model (SiB) for use within general circulation models. *J. Atmos. Sci.* **43**, 505–531.]

evaporation is a result of differences in albedo, aerodynamic roughness, rooting depth, and interception storage between the forest and the replacement vegetation. Increased albedo leads to less solar radiation and less energy being available for evaporation. Aerodynamic roughness will have an effect on evaporation only when the canopy is wet (in dry conditions the surface resistance dominates the transfer process). However the aerodynamic roughness is also an important parameter in determining the large-scale circulation patterns. The rooting depth specifies the amount of soil moisture available to the vegetation for transpiration. Deforestation is usually accompanied by changes in soil properties and the newly established vegetation cannot access water as deep in the soil as the forest. It is however extremely difficult to estimate the exact value of rooting depth to be used in land surface models, as this quantity is hard to measure. The interception storage capacity of a forest is reduced when the area is deforested. This combined with a reduced aerodynamic roughness leads to a decrease in the amount of water lost by the new vegetation through evaporation of intercepted water.

Changes in atmospheric circulation as a result of deforestation are consequences of highly complex interactions and vary both spatially and temporally. Although the area-average result of deforestation is often a reduction in rainfall, the spatial patterns can be highly variable with even local increases in rainfall in certain regions. Figure 7 predicts that the impact

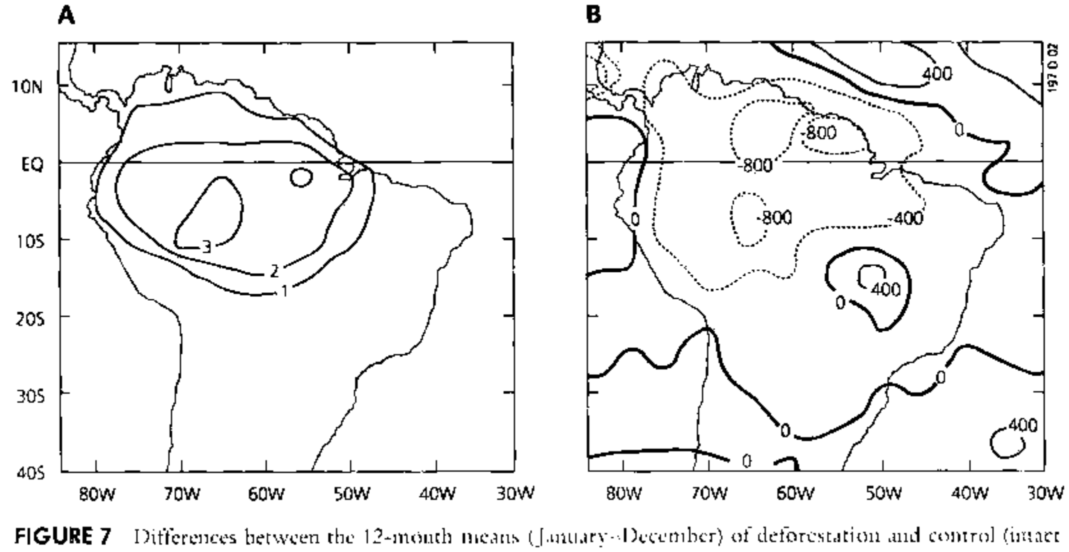

FIGURE 7 Differences between the 12-month means (January–December) of deforestation and control (intact forest) of a GCM experiment. The differences are shown as deforested minus control. (A) Surface temperature (K). (B) Precipitation (mm). [Redrawn with permission of the American Meteorological Society from Nobre *et al.* (1991). Amazonian deforestation and regional climate change. *J. Clim.* **4**, 957–988.]

of deforestation may also be felt in regions far outside the deforested area and this is clearly of importance for agriculture in the neighboring, low rainfall, savannah regions. An increase in surface temperature as observed in most studies is consistent with a reduction in evaporation (less cooling at the surface).

An important question relating to possible changes in climate following deforestation is whether the new climate would favor a vegetation different than that of tropical rain forests, for instance, tropical savannah. As one of the results of deforestation may be more prolonged dry seasons, it is likely that soil moisture plays an important role in determining what type of vegetation may be established after deforestation. For the Amazon basin it was calculated that to a significant extent topical deforestation would be irreversible, i.e., the resulting soil moisture conditions would favor another vegetation type, savannah (called cerrado), in the Southern part of the Amazonia.

The results discussed so far relate mainly to the effect of deforestation of the Amazon basin. Although this is the world's single largest tract of tropical rain forest, it is relevant to ask what the effects of deforestation in Asia and Africa might be. It is likely that the microclimatic effects of deforestation will also happen in these continents, but that the decrease in rainfall is less likely, especially for South East Asia, where rainfall patterns are dominated by large-scale features and the surface temperatures of the oceans. In Equatorial Africa large-scale deforestation may be accompanied by reduction in rainfall similar to those found in Amazonia. Both in South America and Africa these effects may sometimes be masked by variations caused by external effects such as that resulting from changes in the surface temperatures of the Pacific and Atlantic Oceans.

VII. Conclusion

The tropical rain forest presents a unique biome, both in terms of species composition and in microclimate. Substantial advances in our understanding of the hydrology and climatology of these forests have been gained in the past 2 decades. Parallel development in measurement techniques and numerical modeling has increased our knowledge of the role of rain forest in the regional and global climate. However our knowledge and understanding of the interaction between this important biome and the climate is still meager. Because of their size and equatorial position the rain forests of the world are a major heat and moisture source for the global circulation of the atmosphere. The potential regional and global impacts of large-scale deforestation in the tropics require concerted international efforts both to improve our understanding of this biome and to safeguard its future against large-scale devastation.

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Turfgrasses

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Glossary

Artificial turf Synthetic surface (i.e., carpet-like) that simulates a turf

Cool-season turfgrasses Turfgrasses (e.g., Kentucky bluegrass, creeping bentgrass, and tall fescue) that grow most actively in the spring and fall

Mowing height Height of cut above the soil surface; a fundamental practice of turfgrass culture

Turf Closely mowed ground cover, usually comprised of grasses

Turfgrass blend Turfgrass community involving a combination of two or more cultivars of a species

Turfgrass community Composite of individual turfgrass plants that are mutually interactive with their environment

Turfgrass culture Composite of primary and secondary cultural practices involved in growing turfgrasses for their intended purpose, such as lawn, golf course greens, sports turf, or other purposes

Turfgrass mixture Turfgrass community comprised of two or more species

Turfgrass quality Assessment of uniformity, density, texture, growth habit, smoothness, and color of a turf

Warm-season turfgrasses Turfgrasses (e.g., bermudagrass, zoysiagrass, and buffalograss) that grow best in the warm portions of the year; they are usually dormant during the winter and their adaptation is limited by low-temperature injury

Turfgrasses are an integral part of our daily lives. Turfs provide aesthetic and functional value to our landscapes. They contribute to our psychological, physical, and environmental well-being. The cool, clean, and pleasing green environment turfs provide make a pleasant place for work and leisure, but turfs provide more than aesthetics. Turfs dissipate heat, reduce glare, abate noise, minimize soil erosion, eliminate dust and mud, enhance air quality, and contribute to increased property value. Many outdoor recreational and sports activities, such as baseball, croquet, football, golf, lawn bowling, rugby, soccer, softball, and volleyball use turf as their functional surface. Turfs serve as a safety factor on highway rights-of-way, airfields, and correctional facility surrounds.

I. Turfgrass Industry

The turfgrass industry is broader and more complex than first perceived by the casual observer. It involves individuals and organizations sharing a common interest in the production, maintenance, and use of green spaces for aesthetic and functional purposes. In the United States, a number of surveys have contributed to the better understanding of the size and scope of the turfgrass industry in various states. This information has been used to estimate the overall value of the turfgrass maintenance industry in the United States as contributing $25 to 30 billion annually to the economy. However, the true value of the industry comes from the contributions of all types of green areas to quality of life.

Grasses and gardens are found in biblical reference. Lawns were a part of Persian and Arabian gardens, and the Romans adapted the Persian garden concept to their culture. Medieval English literature makes reference to lawns, which were mixtures of low-growing grasses and wildflowers. During the 16th and 17th centuries, lawns became more common in cities located in Great Britain and northern Europe.

Many cities had a common green area that served as a meeting place for civic and leisure activities.

There is some uncertainty about when the care of turfgrass facilities or the manufacture of specific products for turfgrass maintenance began. It has been advocated that the turfgrass equipment manufacturing industry began when Edwin Budding invented and patented the reel-type lawn mower in 1830. Others felt it began in 1618, when the feathered golf ball was invented. Regardless of this uncertainty, golf course development and maintenance has set the historic baseline for the turfgrass industry.

Technological advances for the turfgrass industry have been largely due to development, distribution, and service of products for the maintenance of golf courses. In recent years, maintenance of residential and commercial lawns has had the most growth of any segment of the industry and has had considerable influence on products manufactured to support its needs. Sports fields use both natural and artificial turf surfaces. Artificial turf evolved as a development of the plastics industry. It is commonly used on sports fields, such as indoor and intensively used facilities. Maintenance of natural turf sports fields has become more technical as extremely expensive and multi-use facilities have incorporated the use of natural turfs into their systems. Management of sports turf is a growing part of the turfgrass industry. Millions of individuals worldwide participate in sports and recreational activities, such as softball and soccer, that involve turfgrass surfaces.

II. Turfgrasses

A basic understanding of turfgrasses and the turfgrass plant is needed to ensure their proper maintenance, culture, and use. The geographic distribution and use of turfgrasses are influenced by the species adaptation to temperature and precipitation patterns. Turfgrasses that originated and continue to persist in a particular region are called native species, while those that are introduced to a region and become permanently established are called adapted or naturalized species. Turfgrass species commonly used today evolved from relatively few locations, but have become widely distributed throughout the world. In most cases, the turfgrasses are not native, but are adapted species.

A. Cool-Season Species

Turfgrass species with growth optimums at soil temperatures of 15 to 24° C are called cool-season turfgrasses. Most of these species had their origin in northern Europe and were forest margin species. These grasses are used widely throughout the cool-humid, cool-subhumid, and cool-semiarid portions of the world.

Cool-season turfgrasses grow best in the spring and fall, and their growth and development slows considerably during the summer. There are over 20 species included in this category of turfgrasses (Table I), but only 7 of these species are used extensively as turfs.

Kentucky bluegrass is the most widely grown cool-season turfgrass. It is adapted to a wide climatic region. Kentucky bluegrass forms a dense, medium

TABLE I

Cool-Season (A) and Warm-Season (B) Grass Species Commonly Used as Turfs throughout the World

A. Cool-season species	
Kentucky bluegrass	*Poa pratensis L.*
Canada bluegrass	*P. compressa L.*
Annual bluegrass	*P. annua var. annua L.* *P. annua var. reptans (Hausskn.) Timm.*
Creeping bentgrass	*Agrostis palustris Huds.*
Colonial bentgrass	*A. tenuis Sibth.*
Velvet bentgrass	*A. canina L.*
Redtop	*A. alba L.*
Red fescue	*Festuca rubra L.*
Chewings fescue	*F. rubra var. commutata Gaud.*
Sheep fescue	*F. ovina L.*
Hard fescue	*F. ovina var. duriscula (L.) Koch*
Tall fescue	*F. arundinacea Schreb*
Annual ryegrass	*Lolium multiflorum Lam.*
Perennial ryegrass	*L. perenne L.*
Smooth bromegrass	*Bromus inermis Leyss.*
Fairway crested wheatgrass	*Agropyron cristatum (L.) Gaertn.*
Alkaligrass	*Puccinellis distans (L.) Parl.*
B. Warm-season species	
Common bermudagrass	*Cynodon dactylon (L.) Pers.*
F_1 hybrid bermudagrass	*C. d. x C. transvaalensis Burtt-Davy*
Korean lawngrass	*Zoysia japonica Steud*
Manilagrass	*Z. matrella (L.) Merr.*
Mascarenegrass	*Z. tenuifolia Willd.*
St. Augustinegrass	*Stenotaphrum secundatum (Walt.) Kuntze*
Centipedegrass	*Eremochloa ophiuroides (Munro.) Hack.*
Carpetgrass	*Axonopus affinis Chase*
Bahiagrass	*Paspalum notatum Flugge*
Kikuyugrass	*Pennisetum clandestinum Hochst. ex Chiov.*
Buffalograss	*Buchloe dactyloides (Nutt.) Engelm.*
Blue Grama	*Bouteloua gracilis (H.B.F.) Lag. ex. Steud.*
Seashore Paspalum	*Paspalum vaginatum Swartz.*

textured, high-quality turf when grown in open sunlight. It is variable in texture, color, shoot density, growth habit, disease resistance, adaptation, and cultural practice requirements. It is this variability that leads to its widespread acceptance and use. Periods of drought and high temperature stress can seriously damage Kentucky bluegrass stands by impairing growth and development. Damage is particularly bad when the turf is not adequately hardened to withstand such environmental stress. A properly conditioned Kentucky bluegrass turf can survive an extended drought and recover by initiating growth from crown tissues and nodes located on rhizomes. Kentucky bluegrass is widely used for medium- to high-maintenance lawns, sports fields, parks, golf course fairways and tees, and cemeteries. It is often planted as a blend or as a mixture.

Annual bluegrass is a complex species, which is comprised of annual and short-lived, perennial biotypes. It is about equally accepted as a weed or turfgrass species. It is rarely included as a component of turfgrass seed mixtures. It often invades and becomes a dominant component of closely mowed, intensely fertilized, and frequently irrigated turfs. It forms a fine-textured, dense turf of high quality under proper soil, environmental, and cultural conditions. It grows well in compacted soils, but is highly susceptible to high- and low-temperature stress.

Creeping red, Chewings, sheep, and hard are fine-leaved fescues that form a dense, uniform turf. The fine-leaved fescues have very fine, almost needle-like leaves. They should not be confused with the turf-type tall fescues. Red fescue and Chewings fescue are the most commonly used of these species. They are often used in seed mixtures with Kentucky bluegrass to enhance shade adaptation. As a group, they are best adapted to well-drained, infertile soils. They are not tolerant of high temperatures, but they are very drought resistant.

Tall fescue has undergone considerable improvement in recent years with the development of turf-type cultivars. Prior to their development, the species would have been described as forming a course textured, low-density, bunch-type turf. Recent cultivar releases are darker green and finer textured than the older, forage-type cultivars. Tall fescue is very tolerant of high temperatures and is quite drought resistant. It is also very wear tolerant, but lacks tolerance to compacted soil conditions.

Perennial ryegrass is a bunch-type grass with medium texture and medium to high shoot density. It is similar to Kentucky bluegrass in appearance and is often included in seed mixtures with it. Perennial ryegrass has the most rapid seedling establishment rate of any of the cool-season turfgrasses. It is often included in seed mixtures when rapid establishment is needed. Perennial ryegrasses have excellent wear resistance and are highly tolerant of compacted soil conditions. They are very drought avoidant due to their ability to form a deep, extensive root system, but they are only moderately drought tolerant due to their bunch-type growth. Perennial ryegrasses require medium to high intensity of culture to maintain desired turfgrass quality.

Creeping bentgrass is used primarily for golf greens, tees, and fairways, but is also used for bowling greens, grassed tennis courts, and crochet turfs. It forms a very fine-textured, high-quality turf that tolerates close mowing. It is a long-lived perennial with excellent low-temperature hardiness. Creeping bentgrass tolerates a wide range of soil types and conditions, but prefers fertile, slightly acid, fine-textured soils. It is susceptible to a number of turfgrass diseases and requires careful management to maintain a quality turf.

Several other bentgrass species are used in specific turf situations. Velvet bentgrass forms a very fine-textured, high-quality turf under close mowing. It is not as aggressive as creeping bentgrass, but it is suited for golf or bowling greens, croquet turfs, and elite lawns. Colonial bentgrass is similar to creeping bentgrass except it is not a vigorous, creeping type. It is often used in mixtures with other cool-season turfgrass species for fairways, tees, and fine textured lawns. Redtop forms an open turf of low shoot density. It was once widely used in turfgrass mixtures, but is now considered to be a weed in quality turfs.

Other cool-season turfgrass species, such as annual ryegrass, alkaligrass, and fairway crested wheatgrass are used to meet special needs. Annual ryegrass is used in low-cost turfgrass mixtures, for temporary turfs, and as species in overseeding dormant warm-season turfs. 'Fults' alkaligrass was selected for use on sites where alkaline soils limit growth. Fairway crested wheatgrass is well-adapted to cool, semi-arid regions. It has excellent drought resistance and is used for revegetation of low rainfall sites.

B. Warm-Season Species

Turfgrass species with growth optimums at soil temperatures of 27 to 35° C are called warm-season turfgrasses. Warm-season turfgrasses are used throughout the warm-humid, subhumid, semiarid, and arid regions of the world. They grow best during the warm summer months and generally cease growth and become dormant with the onset of winter. In some cases, dormant warm-season species are sprayed with a colorant to maintain a green appearance, or are overseeded with cool-season species to provide improved appearance, playing conditions, and use.

Thirteen warm-season turfgrass species are commonly used as turfs in their zones of adaptation (Table I). These species have widespread centers of origin, which can be traced to Africa, Asia, or South America. Buffalograss and blue grama grass are native to the Great Plains of North America. The distribution and use of warm-season turfgrasses is strongly influenced by the species' ability to tolerate suboptimal temperatures. Warm-season turfgrasses do not grow well in regions that commonly have early fall or late spring freezes or regions with severe winters.

Relative comparisons between warm- and cool-season turfgrasses reveal that warm-season species are more heat, drought, and traffic tolerant than cool-season species. Warm-season turfgrasses have deeper, more extensive root systems than cool season. Cool-season turfgrasses are more low-temperature tolerant and are less likely to discolor and become dormant than their warm-season counterparts. Cool-season species are most commonly established from seed, while warm-season turfgrasses are often established from sod, sprigs, or plugs. Since these are relative comparisons, it is important to note that exceptions to these characteristics do occur in both species.

Common bermudagrass is found throughout most of the tropical, subtropical, and warm-humid regions of the world. It has a vigorous and aggressive growth habit, spreading both by stolons and rhizomes. It forms a dense turf, but not as fine and dense as that of the F_1 hybrid or improved bermudagrasses. Both species form dense sods, with deep, extensive root systems. Bermudagrasses are quite variable in color, shoot density, leaf texture, and adaptation. Species and cultivars differ in their adaptation to low temperatures. Bermudagrass discolors and becomes dormant under low temperatures and high light intensity conditions. Bermudagrasses with low-temperature hardiness and adaptation to cooler regions become dormant more quickly than those that are considered to be less hardy.

Bermudagrasses are widely used for medium- to high-maintenance turfgrass areas, such as lawns, parks, sports turfs, fairways, tees, and greens. Common bermudagrass is used in low-maintenance areas, like roadsides and utility turfs. Bermudagrasses tolerate close mowing and require medium- to high-intensity culture. They are very tolerant of intense traffic, especially when they are actively growing. The bermudagrasses have poor shade tolerance.

The zoysiagrasses are found predominantly in the warm-humid and transition regions of the world. There are three species that are commonly used for turfs (Table I). These species are native to the tropical portions of eastern Asia. Zoysiagrasses form dense, low-growing turfs of high quality. They spread by rhizomes and stolons, form a tight sod, but have a slow establishment rate. The stems and leaves of zoysia species are stiff and fibrous. They have excellent wear tolerance, but their slow growth rate results in a poor recuperative rate after injury.

The three zoysiagrass species differ in their characteristics and adaptation. Korean lawngrass is the most cold tolerant of the three species, while mascarenegrass is the least tolerant. Mascarenegrass has a growth habit that is more diminutive and slower than the other species. Zoysiagrasses are more shade tolerant than most warm-season turfgrasses. Manilagrass is more shade tolerant than the other species. Zoysiagrasses are used in high-quality lawns, golf course tees and fairways, sports turfs, and general grounds. Mascarenegrass is used for golf and bowling greens in some areas of the world. Zoysiagrasses require low to medium intensity of culture, once they are well-established.

Buffalograss is a warm-season turfgrass that is native to the Great Plains region of North America. It was one of the primary species of the shortgrass prairies. Pioneers settling on the Great Plains used sod of this species to construct their sod homes. Buffalograss is well-adapted to warm, semiarid, and subhumid areas. Prior to the increased use of irrigation on turfgrass sites, buffalograss was the most commonly used warm-season species in the semiarid area. Its use declined, with increased use of irrigated bermudagrass for high-quality turfs. However, in the mid 1980s, development of turf-type buffalograsses renewed interest in their use. Two vegetatively propagated, turf-type cultivars of buffalograss have recently been released, and seeded cultivars are soon to be released. Turf-type buffalograsses spread by stolons to form a dense, fine-textured turf, similar in appearance to improved bermudagrasses. Buffalograss has excellent drought resistance, but has poor shade tolerance. Buffalograss requires a low intensity of culture. It is adapted for use on lawns, golf course fairways and roughs, and general turfgrass sites.

St. Augustinegrass is a warm-season grass that is native to the West Indies. It forms a coarse-textured, low-growing turf that spreads by stolons. It has a vigorous, spreading growth habit, with a medium establishment rate. It is less tolerant of traffic than either bermudagrass or zoysiagrass, but it recovers well from wear injury. St. Augustinegrass has poor low-temperature tolerance. It has a high water use rate and only fair drought resistance. St. Augustinegrass has the best shade tolerance of the warm-season turfgrasses. St. Augustinegrass requires medium- to low-intensity management and is used in lawns and general turfgrass areas in warm-humid regions. It is generally not used on sports turfs or other intensely trafficked areas.

Bahiagrass, centipedegrass, carpetgrass and kikuyugrass are other warm-season turfgrass species that are used on a limited basis or for very specific turf conditions. Bahiagrass is well suited for growth in warm-humid regions, and turfs receiving low-intensity culture. It is used extensively on roadsides in the southern part of the United States. Centipedegrass is native to southern China. It spreads by short, thick stolons and forms a relatively dense turf. Centipedegrass requires similar intensity of culture as bahiagrass. It is best suited for use on lawns and low traffic sites. It is adapted to coastal areas in the warmer parts of the warm-humid regions of the world. Carpetgrass is native to south Central America. It forms a coarse, low-growing turf. It has very poor low-temperature tolerance. Carpetgrass requires a low intensity of culture and is used for lawns and other turf sites that receive minimal traffic. Kikuyugrass is native to east Africa and is used for lawns and golf course fairways and roughs. It has a very aggressive growth habit, spreading by rhizomes and stolons. It can become an undesirable, weed species, when it contaminates a quality turf. Kikuyugrass is very traffic tolerant, but has poor low-temperature tolerance. Its use is limited to the warmer parts of the warm-humid regions of the world.

C. Turfgrass Communities

It is important to have an understanding of turfgrasses and their adaptation. Only adapted turfgrass species will supply a quality, permanent turf. Before establishing a turf, consideration should be given to selecting species and cultivars that are suited to the climate, environment, use, and intensity of culture where they will be used. Turfgrass stands are communities of plants that change composition in response to these conditions.

Communities may be monostands or polystands. Monostands are comprised of a single cultivar of a species. A monostand is limited in its ability to change in response to changing conditions. Polystands are comprised of two or more species, cultivars, or both. A stand with two or more species is termed a mixture, while those comprised of two or more cultivars are called blends. Mixtures and blends provide turfgrass communities with a wider genetic base and better adaptation to changing environment, use, and culture than monostands. Mixtures and blends enhance the potential for maintaining turfgrass quality by minimizing pest problems which increase with time.

III. Turfgrass Establishment

Turfgrasses play an important role in minimizing soil loss from wind and water erosion. This is particularly true during their establishment phase. The longer the establishment period, the greater the potential for wind and water erosion. Poor establishment may also result in a thin, open turf that is easily invaded by weeds. The establishment phase is important to the final turfgrass quality and its long-term maintenance. Turfgrasses can be established vegetatively or from seed. In either case, proper soil preparation, weed control, fertilizing, watering, and post-seed germination or planting care are needed.

A. Seeding

Seeding is the most common means used for turfgrass establishment, especially for cool-season turfgrass species. Proper steps should be followed to successfully establish a turf, ensure rapid stand development, enhance soil stabilization, and attain desired turfgrass quality. These steps include controlling weeds that may persist after establishment; grading the soil to ensure proper surface and subsurface drainage; modifying soil with organic matter, lime, or sand as needed; fertilizing based on soil test recommendations; and finalizing soil preparation for a firm seedbed. Advanced planning is required for proper timing and coordination of these procedures. The same preparation steps are required whether the turf is seeded or vegetatively established.

Successful establishment from seed requires selecting an adapted turfgrass mixture or blend; using quality seed; planting at the proper rate, date, and time;

ensuring good seed soil contact; using proper mulching procedures; and following appropriate postgermination care. Seed can be spread by broadcast and drill-type spreaders or by hydroseeding. Hydroseeding involves disbursing seed and a cellulose fiber mulch with a pressurized stream of water. Unlike drill seeding, hydroseeding does not ensure good seed soil contact. It is best used in regions with uniform rainfall during the establishment phase.

B. Vegetative

Turfgrasses can be established vegetatively by sprigging, stolonizing, plugging, or sodding. Planting turfgrass stolons, rhizomes, or both in shallow furrows or spaced holes is called sprigging. Sprigs are covered to a depth of 15 to 25 mm, and the soil is firmed to enhance contact with the vegetative materials. Sprigging requires less plant material than stolonizing. Improved bermudagrasses are often established vegetatively by sprigging. Stolonizing involves broadcasting stolons over a prepared soilbed, covering them with topdressing, and rolling to ensure good soil contact with the stolons. Stolons can also be applied by hydroplanting, which is basically the same procedure used for hydroseeding. Creeping bentgrass and improved bermudagrasses are sometimes established by stolonizing. Plugging describes the use of small sod pieces to establish a turf. Plugs have a better survival rate, but a poorer establishment rate, than either sprigging or stolonizing. Zoysiagrass, St. Augustinegrass, and buffalograss are often established from plugs.

Harvesting mature turf, including roots, stolons, rhizomes, and soil, and transplanting it to a new site is termed sodding. Sod provides a rapid method of establishment. Sodded turfs are essentially ready for immediate use. Soil preparation for sodding is similar to the procedures used for seeding a turf. Kentucky bluegrass and bermudagrass are turfgrass species that are widely used in the sod industry.

IV. Turfgrass Cultural Practices

A. Primary Cultural Practices

Mowing, fertilizing, and irrigating are primary cultural practices that directly affect leaf, shoot, and root growth and the overall turfgrass quality and performance.

Mowing is fundamental to all turfgrass culture. Turfgrasses species and cultivars differ in their ability to tolerate close mowing. Turfgrasses with spreading, low-growth habits tend to tolerate lower cutting heights than those with erect growth habits. Creeping bentgrass and annual bluegrass can tolerate mowing heights of less than 6 mm. Tall fescue, bahiagrass, and St. Augustinegrass prefer mowing heights of 38 to 76 mm. Turfgrasses have an optimum mowing height range. As the mowing height is lowered below the optimum, tolerance to environmental stress, such as high temperature and drought, decreases.

Mowing frequency influences turfgrass quality, stress tolerance, and function. Golf course greens are mowed close and frequently to enhance their quality and playability. It is not uncommon to mow a creeping bentgrass green five to seven times per week at 3.5 to 4.0 mm. Frequent mowing reduces vertical elongation of the turfgrass leaves and shoots, increases shoot density, and reduces water use rate by enhancing canopy resistance. Mowing frequency should be dictated by the growth rate of the turfgrass. Rapid-growing turfs require frequent mowing. It is generally recommended that no more than one-third of the turfgrass topgrowth be removed with any mowing. For example, a Kentucky bluegrass turf maintained at 50 mm should be mowed when it reaches a height of 75 mm. It is not necessary to remove clippings on home lawns and general turfgrass sites if the appropriate mowing frequency is maintained. Turfgrass clippings contribute very little to thatch accumulation, but do recycle nitrogen, phosphorus, potassium, and other plant nutrients as they decompose in the turfgrass canopy. Clippings are removed from a turf, like golf course greens, if they disrupt its function.

Rotary and reel-type mowers are the most common turfgrass mowers. Rotary mowers cut with a horizontal blade that is rotating at a high speed. Rotary mowers are used extensively on home lawns and general turfgrass areas. Reel mowers provide the highest quality of cut. They cut with a scissor-like action. The reel catches the turfgrass leaf blades and brings them in contact with a sharp, cutting edge called the bedknife. Reel mowers are commonly used on golf course and sports turfs, where a high-quality of cut is desired. Mower operation and mowing patterns also influence turfgrass quality. It is recommended to change direction with each mowing. Changing mowing patterns minimizes compaction stress and reduces turfgrass grain development. Mowers should be kept sharp and in good operating condition.

Turfgrasses require adequate nutrition to perform up to its potential. Turfgrass nutrition influences growth rate, leaf area, depth, and extent of rooting and water use of turfs. Turfgrasses derive most of their nutrients from the soil, but supplemental fertilization is typically needed since soils are often deficient in one or more of the essential elements needed for turfgrass growth and development. Turfgrass fertilization should be based on soil test recommendations. Nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur are required in relatively large amounts, while micronutrients, such as iron, manganese, zinc, copper, molybdenum, boron, and chloride, are needed in trace amounts (e.g., mg liter^{-1}). Turfgrasses are quite responsive to nitrogen, in terms of color and growth rate. This responsiveness can lead to problems, since excess nitrogen fertilization encourages topgrowth at the expense of root growth and reduces turfgrass stress tolerance.

It is important to meet and not exceed the nutritional needs of turfgrasses. Nutrient requirements vary by species and cultivar, length of growing season, intensity of culture, and use. Nutrient availability is influenced by a number of factors, such as soil texture, organic matter content, soil reaction, soil microorganisms, and soil moisture. A thorough understanding of these factors and their interactions is needed to develop an adequate nutritional program and select the appropriate fertilizer materials to meet the nutritional needs of the turfgrass plant.

In many areas, natural precipitation must be supplemented with irrigation to provide desired turfgrass quality and function. Irrigation should be supplied as the plant needs water. Some soil drying between irrigations is desirable. Irrigating too frequently can result in reduced turfgrass vigor and quality. Turfgrass species and cultivars vary in their water use rates. St. Augustinegrass and tall fescue can use in excess of 12 mm of water per day. Buffalograss, zoysiagrass, bermudagrass, and Kentucky bluegrass have shown promise for water conservation through reduced water use rates. Turfgrass water use rates can be altered by changes in environment, soil water content, cultural practices, and pest damage.

The turfgrass irrigation industry is relatively new, when compared to the field crops industry. Its evolution to automated, underground system with a high degree of sophistication has been fairly rapid. Permanent, underground systems are preferred for most turfgrass sites. These systems do not disrupt the mowing, function, and appearance of the site. Sod production requires the use of aboveground systems due to sod harvest concerns. It is important to consider the type of irrigation system, quantity and quality of water available, source of water, and frequency of irrigation, as well as the turfgrass species and cultivars, soil type, topography, length of growing season, intensity of culture, and use, before initiating an irrigation program. Turfgrasses should be irrigated based on their water use rates and not on a set schedule. It is best to irrigate in the early morning (0400 to 0800 hr), when evaporation rates are low and wind does not disrupt irrigation pattern uniformity.

B. Secondary Cultural Practices

Soil cultivation, topdressing, thatch removal, and vertical mowing or grooming are cultural practices that are employed on an as needed basis. They play an important role in maintaining turfgrass quality and function. Secondary cultural practices are often interactive with primary practices in influencing the overall quality of the turf.

Turfgrass soil cultivation includes the practices of coring, slicing, and spiking. These practices are used to minimize the negative effects of soil compaction, improve soil aeration, and enhance water infiltration rates. Coring is the most commonly used practice. Turf sites, that receive intense traffic or are grown on high clay content soils require annual coring to maintain a quality turf. Slicing and spiking are used mostly on golf and bowling greens, or sports turf, since they can be practiced more frequently than coring and with minimal disruption to the playing surface.

Topdressing is the distribution of a light layer of prepared soil medium over a turfgrass area. Topdressing is most commonly practiced on golf course greens, bowling greens, and sports turfs to smooth the playing surface, reduce thatch, cover sprigs and stolons in establishment, modify soil, and provide winter protection. The topdressing material should match the underlying soil medium as closely as feasible. Frequency of topdressing is dictated by the growth rate of the turf and the need to maintain a smooth, uniform playing surface.

Thatch is a tightly intermingled layer of living and dead plant material located between the soil surface and the turfgrass canopy. It has detrimental effects on turfgrass quality and performance, when it accumulates to excessive amounts. On home lawns an accumulation of 13 mm or more is considered to be excessive. Some problems associated with excess thatch accumulation include reduced heat, cold, and drought resistance; reduced wear tolerance; increased disease and insect problems; susceptibility to scalping injury and localized dry spots; and loss of playing surface uniformity due to foot printing effects. Thatch is best controlled through sound cultural practices and approaches that encourage biological breakdown. Topdressing and core cultivation are beneficial cultural practices used to manage thatch accumulation. Power raking helps reduce thatch when it accumulates to excessive levels.

Vertical mowing is used for thatch removal (e.g., power raking), renovation, and overseeding and control of turfgrass grain in golf course and bowling greens. Vertical mowing is also referred to as grooming, particularly when used on golf greens to enhance putting surface uniformity.

C. Pest Management

Insects, diseases, weeds, nematodes, and certain vertebrate pests can cause considerable damage to turfs and reduce turfgrass quality and function. Use of adapted turfgrass species and sound cultural practice systems favor the competitive advantage of the turf over pests and reduces their ability to influence stand quality and composition. Weeds disrupt the uniformity of turfgrass stands. Their appearance in a turf is often an indicator of poor cultural practices, unfavorable environmental conditions, disease, insect damage, or a combination of these factors.

Pests may inevitably become a part of the turfgrass ecosystem with time. Keeping these pests below damaging levels becomes a part of management through the use of cultural practices, pesticides, and biological controls in a systems approach. There is a growing interest in the use of integrated pest management approaches to reduce the negative impacts of pests on turfgrass quality and function. Knowing the turfgrasses being grown and their potential pest problems and understanding the biological and environmental factors that influence both the turf and pests are essential approaches in preventing pests from reaching unacceptable levels. [*See* INTEGRATED PEST MANAGEMENT.]

V. Future Trends and Developments

Turfgrasses have been commercially recognized since before World War II, but the industry's growth and development accelerated after the war. This growth has continued into the nineties. It is estimated that the turfgrass industry contributes in excess of $25 to 30 billion annually to the United States economy. The growth of the turfgrass industry in the United States is due to societal demands, increased leisure time, and greater discretionary income. These trends are continuing and are increasing on a worldwide basis. There is particular interest in the game of golf, with a growing number of golf courses being developed in European and Asian-Rim countries.

The turfgrass industry in the United States is undergoing change. Golf course development has been relatively stable since the early seventies, but demand for the game continues to exceed the development of new facilities. The lawn care service experienced tremendous growth and development through the late sixties and mid seventies, but this growth seems to have peaked in recent years. Sports turf maintenance is a growing segment of the industry at the present time. Environmental concerns are paramount throughout the industry. There is an increasing emphasis on the use of integrated pest management and water and energy conservation practices. These trends are likely to continue for the near future.

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U.S. Department of Agriculture: A National System of Agricultural Research

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Glossary

Biotechnology Set of tools (including techniques of recombinant DNA, tissue culture, gene transfer, embryo manipulation, and bioprocess engineering) that allows scientists to understand and manipulate life processes at the molecular level

Cooperative agreement Research contract between USDA and other entities for research supported financially by both parties for their mutual benefit

Formula funding Appropriated by Congress, administered by USDA, and distributed to the states based on the state's portion of the United State's rural and farm population; state matching of formula funding on a dollar-for-dollar basis is required; the Hatch Act program funding the state agricultural experiment stations and the McIntire–Stennis Cooperative Forestry Research Program are two of the formula-funded programs

Gene mapping Determination of the relative locations of genes on a chromosome

Genetic engineering Steps required for identifying, isolating, and transferring a desired gene from one organism to another; commonly involves transfer from one species to another

Genome Complete genetic code for any individual organism; the genetic sum of its DNA

Intellectual property Products developed through intellectual rather than manufacturing processes; it includes novel conceptual, physical, or compositional processes resulting in unique products that may be patented or copyrighted (e.g., Unique plants, animals, and microbes developed through the use of genetic engineering; computer programs; musical compositions; and books and manuscripts)

Peer review Review of research proposals in a particular scientific area by a panel of experts in that area; for example, a project requesting federal funding is "peer reviewed" and recommended by a scientific panel prior to the awarding of any funds

Precommercial Refers to the late stages in the research process prior to the development of any potential commercial application

Special research grants Funds appropriated by Congress and distributed by USDA to experiment stations or other research institutions for specific research projects at specific locations

Strategic planning derived from the military use of the word "strategy," it includes the definition of mission and objectives—how the company or public institution sees its purpose and where it wants to go—and determination of the best means to achieve those goals at a broad level

Value-added Economic idea that traces the final value of purchased goods and services to see where the value was created or increased; in a primary industry such as agriculture, added value often comes from processing harvested products (e.g., converting corn into ethyl alcohol fuel; using starch from potatoes to make biodegradable plastics)

For more than 100 years, the U.S. Department of Agriculture (USDA) has been the initiator, the incubator, and the launch pad for a national system of agricultural research and development. The reason is simple. It takes cooperation to address the complex problems of real life. The USDA research programs, both those conducted by Department employees (in-house researchers) and those done outside the Department (extramural researchers), are part of a complex mosaic that together with other federal, university, and private research programs form a national system of agricultural research and development that cooperatively addresses problems in the areas of agriculture production, food, fiber, fuel, and protection of the environment. The strength of the U.S. agricultural research system lies in the tight, productive cooperation among government, the universities, and industry, according to a Washington Post editorial in 1992. The editorial noted that over the past century, this combined effort has led to possibly "the most successful research and development program in the country's history."

I. Background of USDA-Supported Research

The development of publicly supported agricultural research is an exciting and successful chapter in U.S. history. No other area of state–federal relations has been more effectively integrated over the years. Historians note that the forces of policy and research joined program development in making agriculture one of the most productive sectors in the country.

A. Land-Grant Colleges Created

There have been several key actions that set the stage for the creation of land-grant colleges. By the time the Constitutional Convention convened in Philadelphia in 1787, there had been colleges and seminaries dedicated to classical studies for more than 150 years. But it was not until the 1840s when Jonathan Baldwin Turner of Illinois proposed establishing colleges dedicated to agriculture and the mechanic arts that the idea of applying academic science to the resolution of real world problems was born. This was a new concept in education. [*See* EDUCATION: UNDERGRADUATE AND GRADUATE UNIVERSITY.]

Despite a raging Civil War, this proposal eventually was passed by both Houses of Congress and signed into law by President Abraham Lincoln on July 2, 1862. The law became known as the Land Grant Act of 1862 or the First Morrill Act, named for U.S. Representative Justin Smith Morrill of Vermont.

To finance this endeavor, the Act provided for the sale of public land. The money from the sales was invested as an endowment to finance the establishment of at least one college in each state to teach agriculture and mechanic arts without abandoning other scientific and classical studies. This combination of liberal arts and practical education became known as the land-grant college ideal.

B. Congress Creates Agriculture Department

Concomitantly with the establishment of land-grant colleges, Congress established a government agency to look after the interests of farmers. This idea had been a persistent one since George Washington's days as president. But Congress turned down Washington's proposal and even when it finally established the U.S. Department of Agriculture in 1862, the new department was not given cabinet status. That came after a later battle. The department's original mission was to educate and investigate in areas connected with agriculture. [*See* GOVERNMENT AGRICULTURAL POLICY, UNITED STATES.]

Today, USDA, as a cabinet-level department, not only operates federal research laboratories while supporting university-based research, but also operates two of the country's largest social service programs. It administers the nation's largest public recreation program through the Forest Service and the gigantic food stamp and commodity programs.

In the 1860s, Americans were undergoing a period of intellectual awakening that advanced the cause of education, particularly practical education for an agrarian, but rapidly industrializing young country. And together the newly created land-grant universities and the Department of Agriculture met the demand with vigor.

C. Historically Black Land-Grant Colleges Created

With time it became clear that in some states some Americans were excluded from the land-grant institutions. Justin Smith Morrill, author of the First Morrill Act and by then a senator, set about correcting that oversight. Although allowing for dual educational systems that separated institutions on the basis of race, the Morrill Act of 1890 provided the basis for a second set of land-grant institutions later referred to as the historically black land-grant institutions or the 1890 institutions.

This Second Morrill Act codified the principles of the first piece of legislation, but added the principle of equal access to all citizens. The 1890 institutions joined by Tuskegee University turned out to principally serve the African American students of the South and the East.

D. Agricultural Experiment Station System Created

The idea of institutions of higher learning dedicated to meeting the needs of the common man was an excellent idea, unique to this country, but it was not nearly enough. The country needed institutions that engaged in the genesis of new knowledge, and transmitted that knowledge to every community in America. This need led to the establishment of state agricultural experiment stations (SAES). The first two were established in the states of Connecticut and California in 1875, to be eventually followed by stations in all other states and territories in subsequent years. The stations were dedicated to helping the farmers, ranchers, homesteaders, and citizens in general make the best use of food, fiber, fuel, and forest resources, and to increase land productivity in producing such resources. [*See* AGRICULTURAL EXPERIMENT STATIONS.]

Individual stations were a good idea, but an organized national system was needed. U.S. Representative William H. Hatch of Missouri, then chairman of the House Agriculture Committee, authored an act in 1887 to establish in conjunction with the land-grant colleges and universities, a national system of federated yet independent state agricultural experiment stations. This action created a system of national funding for these stations.

E. USDA Creates Agency to Work with the States

In 1888, USDA created an office to fulfill federal obligations under the Hatch Act. Although it has undergone several reorganizations, today that office works closely with a system of 59 experiment stations in the 50 states and several U.S. territories. This agency administers USDA's extramural research grants programs for research carried out by non-USDA scientists. It also works with non-land-grant colleges and universities as well as private industry.

F. Cooperative Extension Service Created

Over the years, disciplines of home economics, forestry, veterinary medicine, and many other areas have become integral parts of the experiment station system. But the new knowledge did not do much good sitting on a shelf. It had to be transmitted to the people who could use it. This need led to the idea of literally placing an extension of the land-grant university in every county in the United States. That idea was codified in the Smith–Lever Act of 1914 which created the Cooperative Extension Service system. The program is a cooperative effort of states, counties, and the USDA. [*See* COOPERATIVE EXTENSION SERVICE.]

Unfortunately, the 1890 Institutions essentially were left out of the original funding for research and extension. It was not until the 1960s that a meager amount of funds was allocated for their use. This support for the 1890 Institutions was strengthened by the passage of the Evans–Allen Act, which for the first time brought significant amounts of money to the 1890 research programs. The program was further strengthened in Farm Bills passed by Congress beginning in 1977.

II. Organizations and Missions

There are a number of organizations focusing on agricultural research including private laboratories operated by endowments, grants, or other funding mechanisms; USDA laboratories; non-USDA federal laboratories; and the laboratories of universities and industry. One of the most important tasks in developing a national system of agricultural research is matching these organizations and missions to the identified needs. This is discussed further in Section II.E.

A. USDA Laboratories

While USDA has for more than a hundred years been in the business of supporting university-based research, it also has been operating its own research facilities.

By directly engaging in research through these "in-house" laboratories, research studies can be conducted that address national and regional issues, including those responding to the needs of the USDA regulatory agencies such as the Food Safety Inspection Service and the Animal and Plant Health Inspection Service.

This plural system allows enormous flexibility in addressing multiple agricultural needs.

B. University Laboratories

The second form of research supported by USDA involves university-based laboratories engaged in a Federal–State partnership research effort. In this arrangement, federal funding for research from USDA is generally matched with state appropriations to support agricultural research at state agricultural experiment stations, forestry schools, veterinary colleges, and home economics colleges, located mostly at the nation's land-grant universities, as well as the 1890 institutions. The USDA administers these extramural research grants programs.

With this arrangement, another dimension—the state perspective—is added to the national system for agricultural research. Together, these efforts promote national, regional, and state perspectives within the national research system while also creating a direct affiliation of the research system with undergraduate and graduate education.

Scholars of research administration point out that this research–education hybrid is virtually unique to the U.S. system, and is one of the primary reasons American agricultural technology has been so productive.

C. Private Laboratories

USDA laboratories and the Federal–State research partnership are not the only players in the success of agricultural production. Private laboratories also conduct research, either directly within corporations or through sponsorship from diverse sources of funding (e.g., philanthropic foundations, grants, and contracts for research).

A notable example of private laboratories is the Boyce Thompson Research Institute in Ithaca, New York, which operates as an independent, private research laboratory funded through an endowment and external grants.

Other private laboratories include those major corporations conducting proprietary-interest research (e.g., Monsanto, DuPont, Pioneer Seed Co.). These private laboratories also sometimes engage in cooperative research with USDA laboratories and university-based laboratories.

D. Non-USDA Federal Laboratories

In addition to USDA laboratories, other federal laboratories make significant contributions to the body of knowledge in agricultural science. The Environmental Protection Agency, the Department of Interior, and the Department of Energy are federal agencies with laboratories conducting research with agricultural applications. Other federal sponsors of research relating to agriculture include institutions such as the National Science Foundation, the National Institutes of Health, and the Agency for International Development. These federal agencies provide grants to research scientists to conduct research both directly and indirectly related to agriculture.

E. Cooperative Planning

With so many different agricultural research partners, one of the great challenges of agriculture administration is matching activities to institutional mission. There is the constant need to guard against duplication and redundancy so that resources are not wasted. There also is a need to maintain constant vigil to make sure that knowledge gaps do not appear through inattention to emerging problems.

Consequently, communication among the research system's components is paramount in identifying strategic issues and developing plans appropriate to individual missions, resources, and need. Some of the oversight for this is provided at the federal level through the National Science and Technology Council, which is administered through the White House's Office of Science and Technology Policy. This council uses working groups to identify new areas of research and to provide government-wide initiatives for areas in need of additional national emphasis.

At the nonfederal institutional level, considerable attention is focused on policy coordination through the Experiment Station Committee on Organization and Policy (ESCOP), an arm of the National Association of State Universities and Land-Grant Colleges. The ESCOP planning and budget process annually addresses program priorities and funding needs, all in collaboration with the U.S. Department of Agriculture.

Individual USDA agencies also engage in strategic planning and priority setting. The intramural research arm of the USDA is noted for its elaborate, 6-year, rolling plan and the heavy involvement of its National Program Staff in coordinating the agency's research activities at multiple levels. As a consequence, policy, budgets, and programs are continuously reviewed within and between agencies, across agencies, and within regions to derive appropriate plans.

F. Stakeholders Get a Voice in Agricultural Policy

As a countercheck to this system, the Department of Agriculture uses the Joint Council on Food and Agricultural Sciences and the Users Advisory Board to gather information from the "stakeholders" in agricultural research to assure that real world priorities and needs are being met and that resources are allocated appropriately. Recently the USDA established the Agricultural Science and Technology Review Board authorized in the 1990 Farm Bill to provide further guidance to the Department's setting of the research agenda. Additional checks are provided through review of Regional Research plans and allocations by the Committee of Nine, an advisory body established through the Research and Marketing Act of 1946 to recommend regional projects worthy of receiving funding. USDA also uses scientific peer-review panels to assure the quality of the science being proposed by individual investigators.

As a consequence of this constant oversight, the Department of Agriculture can assure Congress and the public of the quality of research programs and that resources are being directed to real needs.

III. USDA Research Programs

USDA-supported research programs seek to provide technology appropriate to the entire spectrum of production and use of food, fiber, and feed. For this reason, USDA's research programs focus on:

- Plant and animal systems of interest to production agriculture
- Human use of the products of agriculture
- Appropriate use of natural resources and the protection of the environment as it relates to agriculture
- New products and processes for the harvested products of agriculture in ways that would enhance value-added and utilization
- Economics of markets, trade, and policy to provide an economically stable and profitable agricultural system

Each of these areas of investigation are studied, in varying degrees, by in-house USDA laboratories and university-based laboratories in the Federal–State partnership.

A. Plant Systems Program

The continuous improvement of crop and forest species for agricultural production requires a basic understanding of the biology of the plants, the opportunities for the application of new knowledge, and problem-solving research that can deal with site-specific problems such as crop weeds, insect pests and diseases, climate variables, and differences in crop productivity attributed to soil.

Of primary interest in today's agricultural research agenda is the application of the new tools of molecular biology to understanding of the plant genome structure and to develop the tools to precisely move genetic traits between species through use of genetic engineering. Genomic mapping and genetic engineering offer new approaches to complement more conventional research methods intended for the improvement and cultivation of agriculturally important plants. As a consequence, the spectrum of USDA-sponsored plant system research activities ranges from fundamental studies at the molecular level to very applied problem solving at the farm level.

B. Animal Systems Program

Animal agriculture will continue to be an important component of U.S. agricultural production. However, the interests of consumers and the nature of the problems of animal production systems continue to evolve, as food preferences shift and knowledge is gained by consumers on desirable dietary habits.

Considerable research attention is now being focused on the application of the tools of biotechnology to animal improvement and well-being. Fundamental research investigations into genetic transformation systems, the use of hormones to regulate growth, and the genetic engineering of animal vaccines to control animal disease are some examples of today's animal science research that is looking to better provide for consumer needs and animal production requirements. Physical resources for conducting such research include facilities at SAES and major USDA laboratories that have specialized animal research facilities.

C. Nutrition, Diet, and Health Program

The consumption and use of the products of agriculture directly affect the nutritional status of the consuming public. The growing American interest in fitness and proper dietary practices has emerged as a defining force in the marketplace and in daily individual behavior. To meet these consumer expectations, agricultural research is devoting considerable attention to human nutrition and to diet and health relationships to better serve public expectations.

The quantity and quality of food consumed, the presence or absence of contaminants, postharvest treatments, and the preparation of foods are some of the types of research supported by the Department of Agriculture through its five human nutrition laboratories and the Federal–State partnership. The spectrum of these research activities extends from fundamental investigations to very practical studies aimed at bringing the frontiers of science to solutions of real problems.

D. Natural Resources and the Environment Program

The Department of Agriculture's research interests include stewardship of natural resources and protection of the environment. Research into the sustainability of agricultural production systems, the management of forests, and the maintenance of water, soil, and air quality are all aspects of USDA-supported agricultural research.

E. New Products and Processes Program

USDA is also interested in research that would place higher value on harvested products through manufacturing and processing to make new or altered products. The production of biodegradable polymers from cornstarch, pulp paper made from kenaf, the development of biofuels, and similar advanced technologies continue to receive concerted research attention from USDA.

F. Markets, Trade, and Policy Program

The development of agricultural product markets (both domestic and international), the fostering of trade, and the impact of policies that affect U.S. competitiveness in a global economy are also topics researched by USDA through its extended network. These research activities are considered important components in establishing U.S. agricultural product competitiveness.

IV. USDA Funding Mechanisms

USDA funds outside research in several different ways. The base funded programs are those programs funded by Congress for state experiment station and land-grant university support. These programs include the Hatch Act Programs, the McIntire–Stennis Cooperative Forestry program, the Evans–Allen program for the 1890 institutions, and a program of animal health and disease research. These programs use federal dollars, in combination with state funding, to create a basic level of support for programs addressing state and local needs. They allow for start-up research efforts by new scientists as well as for collaborative regional research ventures. Funding for several of these programs is distributed on a formula basis tied to the state's rural and farm population.

Targeted special grants programs are aimed at specific research problems in a given part of the country, while competitively awarded grants fund the best agricultural science as judged by peer review, regardless of institution, location, or specific area of scientific investigation.

USDA, particularly the in-house research programs, also uses cooperative agreements to support both science and scientists in mutually advantageous arrangements with universities or other institutions.

V. Reporting Accomplishments

USDA maintains a number of public information programs aimed at informing both the users of agricultural science information and the consumers of agricultural products about the scientific breakthroughs generated through its in-house laboratories and through its extramural grants programs. The university system also reports research accomplishments on a regular basis.

Publications, audio and videotape programs, and other methods are used to provide information to specific groups as well as the news media. In addition, USDA maintains a number of online computer databases that provide information directly to subscribing groups. The Computerized Information Delivery Service (CID) operated by the USDA Office of Government and Public Affairs delivers more than a million lines of data monthly directly to subscribers ranging from news media outlets to state farm bureaus, private corporations, consumer groups and other online database services. The Research Results Database, available through the USDA Cooperative Extension Service, provides monthly updates on recent research results from the Agricultural Research Service and the Economic Research Service.

One of the largest research databases is the Current Research Information System (CRIS), maintained by the Cooperative State Research Service. The system maintains information on more than 30,000 ongoing and recently completed agricultural and forestry research projects in the United States. The research described in the database includes projects conducted or sponsored by USDA's research agencies, the state agricultural experiment stations, state forestry schools, land-grant colleges of 1890, U.S. schools of veterinary medicine, and participants in the Department's competitive grants program. Data are available through direct retrieval services to scientists at CRIS-participating institutions and to the public through commercial online files. Information on latest advances in USDA research is available through TEKTRAN (Technology Transfer Automated Retrieval System). This system was especially designed for direct access to research discoveries by agribusiness firms.

VI. Program Planning for the Future

USDA's vision for the future takes into account the need to constantly involve the stakeholder. For agriculture, the stakeholders represent different sectors, ranging from farm and ranch communities to the consumers of both raw and processed agricultural products. There also are a number of agricultural service sectors that provide input into agricultural production. These views represent a critical perspective necessary for developing USDA's agricultural research agenda.

Each sector has its own perspective, particular needs, and priorities. Involving these "users" in the planning process provides a mechanism for continual adjustment in the USDA's research program.

In addition to sampling the stakeholders' perspective, considerable communication is needed with the USDA's partners in other federal agencies to help select the priorities. The Department does this through a variety of mechanisms, including interagency committees, scientific meetings, and dialogue with professional societies to provide needed communications.

VII. System Effectiveness

From its origins as a minor agency advocating science and progress for farmers in 1862, the USDA grew to cabinet level status surrounded by an extensive network of state and county agricultural program professionals. Farmers at the grassroots level pressured for cabinet status because the early work of USDA in partnership with the land grant colleges and state agricultural experiment stations, plus the growing importance of international trade, helped transform the agricultural sector.

Over the past 100 years, the farm population has continued to decline as a percentage of the general population. This means that farm interests must continue to be reconciled with the interests of an increasingly urbanized nation. These alliances often mean that new partners do not necessarily understand agriculture's historic, public sector mission.

In addition, the agricultural establishment has added significantly to its social agenda, but the resulting new alliances between traditional farm interests and the new partners who have gained a voice in agricultural policy are often shaky. Competition is often fierce for scarce federal dollars among environmentalists, consumers, the poor, retailers, agribusiness, farmers, university and federal researchers, commodity groups, and others.

On the road to modernization, farm politics has defied broader traditions of limited government in an essentially laissez-faire, or market-oriented, economy by calling for interventionist public policy. But successes in agricultural development have often been matched by a harsh measure of failure. Problems of commodity surplus occur and with them low prices persistently return to drive less successful producers from the sector leading to loud cries from farm policy critics.

Now, some critics charge, the system of organization originally needed to reach and establish direct relationships with farmers creates problems in transacting new business. The reason, according to Theodore Schultz, Nobel Laureate in economics, is the large number of intertwined agricultural organizations crisscrossing America from the most remote county seat to Washington, DC. Each layer, he said, adds costs and regulation to the action of doing business.

A 1991 General Accounting Office (GAO) report to the Secretary of Agriculture seems to back up some of Dr. Schultz's assessment. That report said, "USDA's organizational structure—essentially unchanged since the 1930s—is not responsive to the new challenges facing the Department."

Among the primary challenges of the 1990s is the development of new industrial uses for traditional agricultural products, many analysts say. Turning corn into fuel and potato starch into plastic substitutes are just the beginning. But critics charge those new challenges will not be met unless there are corresponding changes in rules, policies, practices, procedures, and organization.

Some changes seem inevitable. Even before the GAO report was released, USDA had embarked on an internal review of its organization and structure. The results of that assessment and other assessments probably will bring many changes in the 1990s. Although the public agricultural enterprise has been enormously successful in the past, critics charge that it also must become a more equal partner with industry in the development of new ideas. For every dollar spent in the laboratory on research, it takes 10 dollars to develop the research, and 100 dollars to bring production of the product on line. Since these preproduction tasks can take 10 to 15 years to complete, a private–public partnership is essential, advocates charge.

Some advocates for agricultural policy changes say one of the biggest needs is for an institutional means of splitting the costs of product development between government and the private sector, especially nonfarm, small businesses. A second major factor is the number of regulatory agencies scrutinizing each product before it goes on the market. And finally, there must be a complete assessment of the degree of consumer and environmental risk that can be associated with any product.

The variety of funding mechanisms, the cooperative planning efforts by USDA, and the working relationships between various public and private laboratories including in-house USDA laboratories, university laboratories, and private and non-USDA federal laboratories seem to offer real solutions to those scientific and policy dilemmas.

A. Policy Changes Affecting Research

The emerging national recognition that public and private research in the United States have functioned differently has led to the conclusion that public institutions, such as the USDA and universities, should be patenting living material to be licensed to private industry. The intention of such patents would be to provide better linkage between the public and private sector agricultural research communities, and thus meet one of the stated objectives of U.S. agricultural research: to get research results into use.

In the past, a distinction was made between precommercial and commercial agricultural research. Public laboratories primarily focused on precommercial investigations, allowing any scientific discoveries to then "transfer" to private entities for commercial development. This process of "technology transfer" has now come under question as the United States reexamines its competitive standing in global trade.

The previous open system of public research provides no assurance that primarily U.S. companies will necessarily benefit from the research paid for by American tax dollars. Increasingly, public institutions may focus on areas leading to commercial development. The Patent and Trademark Act of 1980 gave universities the rights to inventions developed under federal grants and contracts. Federal scientists also are able to secure patents for government-sponsored work.

Recent legal decisions giving "inventors" the right to patent living organisms also have caused complications. Prospects for patenting plants and animals has caused some institutions (e.g., universities) to move conceptually closer to commercial applications. The patenting of living material limits access for other scientists. As a result, the sharing of information and biological materials may be disrupted. This is a major concern for much of the scientific community, which remains uneasy over the scientific consequences of these ethical and legal choices regarding patenting plants and animals.

B. USDA's Role

The USDA will undoubtedly play a major role in establishing the final balance between an open scientific system in the public sector and the intended benefits of patenting living material. This process will likely take place through discussions among the stakeholder sectors, the scientific community, the private sector, and other science-related disciplines that contribute to agriculture's research effort (e.g., ecology, human medicine, biological sciences). The final resolution should represent a combination of choices that will provide societal benefits that outweigh the negative consequences.

In the dynamics of an ever-evolving system of agricultural science, USDA will play a central role as a direct participant and as a facilitator of actions by other institutions. Each of the partners in this national agricultural research system will contribute equally to the cornucopia that feeds not only Americans, but also a considerable portion of the world.

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U.S. Farms: Changing Size and Structure

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Glossary

Farm Establishment that sells or would normally sell $1000 or more of agricultural products annually
Net cash farm income Receipts from sales of agricultural products plus government payments received less cash costs of production
Net worth Total assets minus total liabilities, also sometimes called "equity"
Off-farm income Income generated by farm operators or their family members in activities which are not related to the production of agricultural products
Return on assets (ROA) Net farm income plus interest expenses minus a charge for unpaid labor, all divided by total farm assets; it is a percentage return to assets used in agriculture
Return on equity (ROE) Net farm income minus a charge for unpaid labor divided by total farm net worth or equity; it is a percentage return to the money invested by owners of agricultural assets
Vertical integration Process of combining two or more stages of production under the control of a single firm

Change has been an important feature of U.S. farms since the days of the homesteaders. As the West was settled, farm numbers expanded rapidly while in recent decades the number of farms has plummeted and farm size has increased. Ownership patterns also continue to change, although private ownership of land has remained a guiding principal. The financial performance of farm firms has also changed over time and new patterns continue to emerge. Nowhere is change in agriculture more evident than in the growing integration of production, marketing, and distribution of agricultural products. This article focuses on the changing nature of U.S. agriculture and explores possible future directions in farm size and structure.

I. Changes in Farm Size and Number of Farms

The U.S. Department of Agriculture currently defines a farm as a place that sells $1000 or more of agricultural products annually. From 1975 through 1990, more than 375,000 farms went out of business with most of the land and other assets being absorbed into larger farms (Table I). Although this decline in the number of farms is significant, the rate of decline is much lower than in earlier years. Land in farms is also decreasing, but at a slower pace than the number of farms—the net result is an increase in average size of farms.

In addition to an increase in acreage, many farms have increased the volume of output through improved production practices and more intensive operations. Another way of measuring farm sizes is through the volume of annual sales or "economic classes" (Table II). The two largest economic classes (gross sales of over $100,000 per year) account for less than 15% of the farms, but nearly 50% of the land farmed. On the other end of the spectrum, the two smallest economic classes (gross sales of less than $5000 per year) account for about 40% of the farms, but less than 7% of the land farmed. Over time, there has been a growing proportion of farms in the larger economic classes. However, part of that trend is due to inflation in prices, since economic classes have not

TABLE I

Farms: Number, Land in Farms, and Average Size of Farm, United States, 1975–1990

Year	Farms[a] (number)	Land in farms (1000 acres)	Average size of farm (acres)
1975	2,521,420	1,059,420	420
1976	2,497,270	1,054,075	422
1977	2,455,830	1,047,785	427
1978	2,436,250	1,044,790	429
1979	2,437,300	1,042,015	428
1980	2,439,510	1,038,885	426
1981	2,439,920	1,034,190	424
1982	2,406,550	1,027,795	427
1983	2,378,620	1,023,425	430
1984	2,333,810	1,017,803	436
1985	2,292,530	1,012,073	441
1986	2,249,820	1,005,333	447
1987	2,212,960	998,923	451
1988	2,197,140	994,543	453
1989	2,170,520	991,153	457
1990[b]	2,143,150	987,721	461

Source: U.S. Department of Agriculture (1991). "Agricultural Statistics, 1990." Washington, DC.

[a] A farm is an establishment that as of June 1 sold or would normally have sold $1000 or more of agricultural products during the year.

[b] Preliminary.

TABLE III

Gross Cash Income from Farm Sources, by Major Component, 1945–1990

	Farm marketings[a]			Percentage of total	
Year	Livestock	Crops	Total	Livestock	Crops
1945	12,008	9,655	21,663	55.4	44.6
1950	16,105	12,356	28,461	56.6	43.4
1955	15,967	13,523	29,490	54.1	45.9
1960	18,989	15,023	34,012	55.8	44.2
1965	21,886	17,479	39,365	55.6	44.4
1970	29,532	20,977	50,509	58.5	41.5
1975	43,089	45,813	88,902	48.5	51.5
1980	67,991	71,746	139,737	48.7	51.3
1985	69,822	74,293	144,114	48.4	51.6
1990	89,623	80,364	169,987	52.7	47.3

[a] Forest products are included in farm marketings prior to 1978.

been adjusted to maintain a constant purchasing power. [*See* PRODUCTION ECONOMICS.]

Changes in the location and type of agricultural production are also common although the balance between livestock and crop production has remained fairly stable over time (Table III). Since 1945, livestock and livestock products have continued to account for approximately 50% of total farm marketings. While there has been some shift in consumer preferences away from beef toward turkey and broilers, sales of livestock as a percentage of total farm sales have not changed much since 1945. The geographic location of various production activities, particularly for some types of livestock, has shifted over time.

The distribution of crop and livestock farms by enterprise type and net cash income, is shown in Table IV. The most common farm type is red meat, but income per farm is much higher on most other farm types. A relatively high percentage of farms in the red meat category are small part-time cattle farms.

A myriad of social, political, and economic forces have generated changes in the number and size of

TABLE II

Percentage of Farms, Land in Farms, and Average Size, by Economic Class, United States, June 1, 1985 and 1990

	Percentage of total				Average size of farms	
	Farms		Land			
Economic class Gross value of sales	1985(%)	1990[a] (%)	1985 (%)	1990[a] (%)	1985 (acres)	1990[a] (acres)
$1,000–$2,499	25.1	22.2	3.8	3.0	67	62
$2,500–$4,999	14.3	13.7	3.6	3.1	112	104
$5,000–$9,999	11.8	11.7	4.6	4.1	176	162
$10,000–$19,999	10.7	11.1	6.8	6.3	283	262
$20,000–$39,999	10.1	12.1	9.4	10.8	417	411
$40,000–$99,999	14.2	14.4	24.3	23.2	760	743
$100,000–$249,999	9.7	10.0	25.5	26.0	1,172	1,198
$250,000	4.1	4.8	22.0	23.5	2,419	2,256
Total	100.0	100.0	100.0	100.0	446	461

Source: U.S. Department of Agriculture (1991). "Agricultural Statistics, 1990." Washington, DC.

[a] Preliminary.

TABLE IV

Distribution of Farms by Enterprise Type and Net Cash Income, 1990

Farm type[a]	Number of farms (thousands)	Net cash income (billion dollars)
Crops		
Cash grain	426	17.1
Tobacco	87	0.8
Cotton	24	3.9
Fruit, vegetables	108	10.7
Livestock		
Red meat	993	15.1
Poultry and eggs	38	5.7
Dairy	169	6.8

Source: Agricultural Income and Finance: Situation and Outlook Report, AFO-45. ERS-USDA, May 1992.

[a] Farm types are defined as those with 50% or more of total value of production accounted for by a specific commodity or commodity group.

TABLE V

Index of Farm Labor Productivity per Hour, Selected Years (1967 = 100)

Year	Index
1938	20
1944	25
1949	33
1954	43
1959	62
1964	83
1969	112
1974	132
1979	198
1984	212
1989	259

farms. Some of the more important factors affecting the number and size of farms are government farm programs, growth in labor-saving technology, and relative incomes of farm versus nonfarm residents. A later section on financial performance will address the issue of relative incomes more fully.

U. S. government farm and food policies have generally attempted to balance public concerns over an adequate and stable supply of high-quality, reasonably priced food with concerns of incomes for agricultural producers. While there is considerable debate over the long-term effects of commodity price support programs, most analysts agree that such efforts have slowed the adjustment process in agriculture. This has resulted in more farms and smaller farms than would likely exist in the absence of such price support programs. [*See* Crop Subsidies; Government Agricultural Policy, United States.]

Disaster assistance and credit programs of the Federal government have also been used to assist financially distressed producers. Again, the long-term effect appears to be one of slowing the transition to fewer and larger farms.

One of the primary reasons for a movement to fewer and larger farms has been the tremendous growth in new technology which is often capital intensive, but labor-saving. Productivity per worker has grown sharply (Table V) and capital employed in agriculture has expanded, while the number of farms has declined. Many factors contribute to this growth in technology including publicly supported research and outreach activities which have made adoption of new technologies virtually mandatory for firm survival. [*See* Energy Utilization; Labor.]

While the above mentioned factors will continue to influence the number and size of farms, other factors may be particularly influential in determining the future directions in the number and size of farms. First, there now appears to be a concerted effort to reduce the large subsidies associated with agricultural production in many of the developed countries of the world. This movement toward lower subsidies in agriculture will create a strong impetus toward "survival of the fittest." The lowest cost/highest profit farms have tended to be larger scale operations. Thus, the trend to fewer and larger farms is likely to continue.

A second factor influencing the future size and structure of agriculture is the aging farm population. The average age of farmers has steadily increased in recent years creating considerable concern over who will serve as the next generation of farmers. As the older generation of farmers retire or scale back their operations, the potential for consolidating farms into larger more efficient units will likely increase. [*See* Rural Sociology.]

Changing consumers preferences, both in terms of choice of geographic areas in which to live and in terms of food consumption patterns, will also influence the size and type of farms. Economic diversification, better communications systems, and improved road systems all contribute to increased financial viability for small part-time farms that rely heavily on off-farm incomes. Changes in consumption patterns, primarily resulting from health concerns, have already created a shift among livestock products and increased the demand for fruits and vegetables. Further changes of this nature can be expected as the population of the United States grows older, and in the process becomes more concerned with healthful diets.

II. Farm Structure and Ownership

There is some concern that U.S. agriculture is being taken over by large-scale corporate farms and that such actions are likely to lead to higher food prices. To explore this issue, it is useful to examine how the ownership and structure of U.S. agriculture have changed over time and how they might continue to evolve in the future.

Table VI illustrates the proportion of farms, acreage, and gross sales by type of organization. As shown in Table VI, sole proprietors account for 87% of all farms, 65% of the acres farmed, and 56% of the total farm sales. Partnerships are the second most common form of business organization accounting for 10% of all farms. Corporations account for only 3% of all farms, but most of these are family-held corporations. Nonfamily farm corporations account for less than 0.5% of all farms, but they do account for 6% of gross sales. Notice also that nonfamily farm corporations tend to rent a much smaller proportion of the land they operate than do family owned businesses.

It is evident from Table VI that rented land is a very significant component of the operation of many farms. Table VII identifies the amount of land in farms and the proportion which is rented. From 1940 through 1964, the proportion of land rented tended to decline; since 1969 the proportion of rented land has tended to increase. Overall, the percentage of land rented has not changed dramatically in the last 40 years. What has changed significantly is the proportion of "tenant operated farms," defined as farms in which the operator farms only land rented from others. While nearly 39% of all farmers in 1940 rented all of the land they operated, this fell to only 11.5% by 1987. This is due in part to the demise of sharecrop farmers in the south and because farm operators have become more interested and more able to own at least some portion of the land they operate.

To evaluate the future changes in farm ownership patterns, it is useful to examine recent data on who is buying and who is selling farmland (Table VIII). While significant regional variation is apparent, the majority of buyers for all farmland are owner-operators. Nonfarmer buyers are also important and in some regions account for over 50% of the purchases. The majority of sellers of farmland tend to be active farmers who either remain in farming after the sale or retire. Note that nonfarmers are also significant sellers of farmland, but in recent years they have purchased more than they have sold. These nonfarmer owners then contribute to the amount of land which is offered for rent.

In examining the patterns of landownership and use, it is important to recognize that from 1940 until 1980, farmland values increased virtually every year. And during the decade of the 1970s, farmland value increases exceeded the rate of inflation by a substantial margin. This history of capital gains generated considerable incentive for the ownership of land and may explain, at least in part, the reasons for the significant decline in tenant operated farms during this time period.

The crash in farmland values during the early to mid-1980s starkly reminded owners that farmland can also decrease in value. The decrease in land values, combined with more modest rates of capital gains after the mid-1980s, has significantly altered the eco-

TABLE VI

Selected Farm Characteristics by Type of Organization, 1987

Farm organization type	Proportion of total (%)			Average farm		Proportion of land leased (%)
	Farms	Acres	Sales	Sales ($1000)	Size (acres)	
Sole proprietor	87	65	56	42	347	43
Partnership	10	16	17	117	768	49
Corporation						
Family	3	11	20	437	1743	43
Nonfamily	<½	1	6	1341	2167	33
Institutional[a]	<½	7	1	107	5396	13

Source: Olaf Kula and Denise Rodgers, "Farmland Ownerhsip and Renting in the United States. 1987." ERS-USDA, AGES 9130, June 1991.

[a] Institutional includes cooperatives, estates or trusts, prison farms, grazing associations, Indian reservations, or institutions run by a government or religious entity.

TABLE VII

Land Rented by Tenants and Part Owners, 1940–1987

Year	Land in farms	Land rented by operators (million acres) Tenants	Part owners	Total	Proportion of land leased (%)	Tenant operators (%)
1940	1,165.1	313.2	155.9	459.1	44.0	38.8
1945	1,141.6	251.6	178.9	430.5	37.7	31.7
1950	1,161.4	212.2	196.2	408.4	35.2	26.9
1954	1,158.2	192.6	212.3	404.9	34.9	24.4
1959	1,123.0	166.8	234.1	400.9	35.7	20.5
1964	1,110.2	144.9	248.1	393.0	35.4	17.1
1969	1,063.3	137.6	241.8	379.4	35.7	12.9
1974	1,017.0	122.3	258.4	380.7	37.4	11.3
1978	1,029.7	124.1	285.3	406.3	39.4	12.7
1982	986.2	113.6	269.9	383.5	38.9	11.6
1987	964.5	126.9	275.4	402.3	41.7	11.5

Source: Olaf Kula and Denise Rodgers, "Farmland Ownerhsip and Renting in the United States, 1987," ERS-USDA, AGES 9130, June 1991.

nomics of land ownership. Many farmers today believe that returns from the rental of land may equal or exceed the returns from owning land, especially if debt financing is required to acquire land. Consequently, equity ownership of land, particularly from nonfarmers and institutional investors has become more popular in recent times. The net effect should be an increase in the nonfarm ownership of farmland combined with a higher proportion of farmland being rented by farm operators.

III. Farm Financial Performance by Size and Structure

The financial position and performance of farms vary greatly by size and structure. Past changes and future directions in size and structure are dictated in large part by financial performance. If large farms generate more operator income and greater returns on equity capital, then changes in direction of larger farms are likely to continue. Likewise, if corporate farms can generate a better financial performance than sole proprietorships, movement toward corporate farming is likely to occur. In this section, the financial performance of farms is examined with the underlying objective of trying to discern how that may impact future changes in the size and structure of farms.

Table IX illustrates the balance sheet for farms classified by the value of annual sales. For the largest size farms (over $1 million in annual sales) total farm assets average nearly $5.3 million with a net worth of over $4.1 million. In contrast, farms with less than $20,000 in annual sales have an average of $229,000 of assets and a net worth of $209,000. Notice that the debt-to-asset ratio tends to rise as size of farm increases.

Estimates of net cash farm income for farms classified by annual sales show that farms in the largest size category averaged well over $1 million in net cash income while farms in the lowest size category had a negative net cash income on average (Table X). Net cash farm incomes vary widely by size of farm and generalizations about low income in agriculture are often too simplistic to be of much value in assessing how the sector is likely to change in the future.

Off-farm income is also an important source of income for farm families, often accounting for more of their total income than farm sources (Table XI). In recent years, the lowest off-farm income was achieved by farms in the middle size sales class while the farms in the smallest size sales class had the largest off-farm income. Thus, economic forces are creating two divergent types of farm firms: large farms which rely almost totally on farm sources of income, and small part-time farms which rely almost entirely on off-farm income.

Overall, financial performance of the farm sector can also be judged in the context of rates of return on assets (ROA) and return on equity (ROE) (Table XII). ROA measures a percentage return to all capital invested in agriculture—the capital provided by the owners as well as the capital provided by lenders. ROE measures a percentage return only to the equity that owners have invested in the business. Ideally, ROE should exceed ROA so that borrowed funds are generating a return higher than the interest cost

TABLE VIII

Farmland Buyers and Sellers, 1989–1991

	Buyer											
	Tenant			Owner-operator[a]			Retired farmer			Nonfarmer		
Region	1989	1990	1991	1989	1990	1991	1989	1990	1991	1989	1990	1991
	Percentage of value											
Northeast	5	9	10	39	31	53	1	1	1	55	59	36
Lake States	17	20	23	60	58	60	1	2	2	22	20	15
Corn Belt	10	11	10	53	60	59	2	2	2	35	27	29
Northern Plains	13	15	12	71	75	72	4	*[a]	1	11	10	15
Appalachia	5	6	6	51	46	46	1	1	1	43	47	47
Southeast	1	1	2	59	64	79	1	*	*	39	35	19
Delta States	7	7	13	41	39	40	2	1	2	50	53	45
Southern Plains	10	9	11	49	61	54	1	1	3	40	29	32
Mountain	7	7	11	61	52	52	1	1	*	31	40	37
Pacific	13	5	3	71	79	76	1	*	2	16	16	19
48 States	8	8	9	54	60	62	1	1	1	37	31	28

	Seller														
				Active farm operator who											
	Estate			Remained in farming			Retired or quit			Retired farmer			Nonfarmer/nonfarm business		
Region	1989	1990	1991	1989	1990	1991	1989	1990	1991	1989	1990	1991	1989	1990	1991
	Percentage of value														
Northeast	8	9	14	31	17	26	25	34	25	13	15	19	23	25	16
Lake States	13	16	18	16	15	17	27	18	18	13	17	21	31	34	26
Corn Belt	31	32	33	16	17	15	14	12	12	10	11	12	29	28	28
Northern Plains	26	30	30	21	15	13	13	16	17	15	13	19	25	26	21
Appalachia	27	18	25	20	18	26	17	22	17	10	12	11	26	30	21
Southeast	13	5	14	51	55	56	16	14	9	6	4	5	15	22	16
Delta States	11	12	14	30	18	31	12	23	13	4	6	9	43	41	33
Southern Plains	24	16	24	25	33	21	14	20	17	7	8	10	30	23	28
Mountain	5	8	7	46	24	34	15	14	17	7	5	9	27	49	33
Pacific	6	4	9	41	57	33	21	21	18	11	4	4	21	14	36
48 States	18	15	20	29	32	28	17	18	15	10	9	11	26	26	26

Source: "Agricultural Resources: Situation and Outlook Report," AR-22, June 1991, ERS-USDA.

[a] *, less than 0.5%.

on those borrowed funds. ROE did exceed ROA throughout the decade of the 1970s (Table XII). During the decade of the 1980s, however, ROA exceeded ROE in most years. This relatively poor financial performance of the farm sector is likely to force continued adjustments and changes in the sector. Farms with the poorest financial performance will continue to be forced out, while the more successful farms will likely absorb the assets into larger, more efficient, and more profitable units.

IV. Emerging Trends in Size and Structure of Farms

Change will continue to shape the size and structure of U.S. farms. Several emerging trends are likely to play a major role in this process. In this section, four interrelated trends are identified and their potential impact on the size and structure of farms is explored.

A. Vertical Integration

Vertical integration is the process whereby various stages of production are brought under the control of a single entity or a closely linked group of entities. It now appears likely that vertical integration will continue to grow and expand in agriculture.

There are already numerous examples of vertical integration within the agricultural sector. For example, some large cattle feeding operations now have slaughtering plants as a part of their combined operations. Some fruit and vegetable packing and canning

TABLE IX

Farm Sector Balance Sheet (Including Operator Households), by Value of Sales Class, December 31, 1990

Item	$1,000,000 and over	$500,000 to $999,999	$250,000 to $499,999	$100,000 to $249,999	$40,000 to $99,999	$20,000 to $39,999	Less than $20,000
				Million dollars			
Total							
Farm assets	82,105	62,546	89,878	195,463	175,160	103,312	287,694
Real estate	50,586	40,047	57,611	132,787	122,249	75,176	224,123
Livestock and poultry	13,404	5,458	7,047	13,473	11,539	6,287	11,884
Machinery and motor vehicles	6,884	5,345	9,460	21,391	18,605	9,339	20,677
Crops stored[a]	2,109	2,320	3,798	7,373	3,633	1,340	1,852
Purchased inputs	446	415	509	708	415	136	213
Household goods	3,335	2,640	3,798	8,755	8,060	4,957	14,777
Investments in cooperatives	3,429	4,811	5,171	5,945	4,286	1,548	2,461
Other financial	1,912	1,510	2,482	5,032	6,374	4,529	11,708
Debt	17,280	12,956	18,750	33,425	25,437	11,618	25,601
Real estate[b]	5,587	5,974	8,855	17,586	14,054	7,479	18,863
Nonreal estate	11,693	6,982	9,895	15,839	11,383	4,139	6,738
Equity	64,825	49,590	71,128	162,038	149,723	91,694	262,093
				Percentage			
Debt-to-asset ratio	21.0	20.7	20.9	17.1	14.5	11.2	8.9
				Thousand dollars			
Per farm:							
Farm assets	5,296	2,291	1,400	913	572	399	229
Real estate	3,263	1,467	897	620	399	290	179
Livestock and poultry	865	200	110	63	38	24	9
Machinery and motor vehicles	444	196	147	100	61	36	16
Crops stored[a]	136	85	59	34	12	5	1
Purchased inputs	29	15	8	3	1	1	0
Household goods	215	97	59	41	26	19	12
Investments in cooperatives	221	176	81	28	14	6	2
Other financial	123	55	39	24	21	17	9
Debt	1,115	474	292	156	83	45	20
Real estate[b]	360	219	138	82	46	29	15
Nonreal estate	754	256	154	74	37	16	5
Equity	4,182	1,816	1,108	757	489	354	209

Source: Economic Indicators of the Farm Sector. National Financial Summary, 1990, ECIFS 10-1. ERS-USDA. November 1991.

[a] Non-CCC crops held on farms plus value above loan rate for crops held under CCC.

[b] Includes CCC storage and drying facilities loans.

TABLE X

Number of Farms, and Net Cash Farm Income, by Value of Sales Class, 1990

Item	$1,000,000 and over	$500,000 to $999,999	$250,000 to $499,999	$100,000 to $249,999	$40,000 to $29,999	$20,000 to $39,999	Less than $20,000
				Thousands			
Number of farms	16	27	64	214	306	259	1,254
				Million dollars			
Total:							
Gross cash income	57,496	21,234	25,779	39,370	24,047	9,000	9,051
Cash receipts from marketings	56,231	19,872	23,125	34,830	21,004	7,759	7,166
Direct Government payment commodities	2,760	3,145	5,288	9,115	5,250	1,794	1,008
Price-support-only commodities	5,634	3,801	5,737	11,456	7,229	2,030	1,329
Nonsupported commodities	47,837	12,926	12,100	14,259	8,525	3,934	4,829
Government payments	436	985	2,130	3,222	1,760	524	241
Farm-related income	829	377	525	1,318	1,283	717	1,644
Cash expenses	38,203	13,780	15.617	24,306	16,119	6,619	9,515
Net cash income	19,293	7,454	10,163	15,064	7,928	2.381	−464
				Dollars			
Per farm operation[a]							
Gross cash income	3,708,945	777,624	401,468	183,937	78,565	34,749	7,216
Cash receipts from marketings	3,627,349	727,763	360,125	162,726	68,623	29,958	5.713
Direct Government payment commodities	178,029	115,158	82,351	42,585	17,151	6,928	804
Price-support-only commodities	363,458	139,212	89,344	53,523	23,619	7,840	1,059
Nonsupported commodities	3,085,862	473,393	188,430	66,618	27,853	15,191	3,850
Government payments	28,096	36,056	33.174	15,055	5,749	2,024	192
Farm-related income	53,501	13,804	8,168	6,156	4,193	2,767	1,311
Cash expenses	2,464,395	504,645	243,201	113,559	52,664	25,557	7,586
Net cash income	1,244,550	272,978	158,267	70,378	25,901	9,192	−370

Source: Economic Indicators of the Farm Sector, National Financial Summary, 1990, ECIFS 10-1, ERS-USDA, November 1991.

[a] Farm operations may have several households sharing in the earnings of the business (for example, partners or shareholders in farm corporations). The number of households per farm tends to increase as farm sales increase.

plants now own a significant portion of the land used to supply their raw materials. Other examples can also be cited.

The primary objective of vertical integration is to assure a more uniform supply of products and a more tightly controlled quality of final products. To the extent that vertical integration succeeds in accomplishing these objectives, the integrated firm may face significant cost advantages over those firms who separate the various stages of production.

TABLE XI

Off-farm Cash Income of the Principal Farm Operator and Family, by Value of Sales Class

Year	$1,000,000 and over	$500,000 to $999,999	$250,000 to $499,999	$100,000 to $249,999	$40,000 to $29,999	$20,000 to $39,999	Less than $20,000
				Million dollars			
Total							
1990	441	708	1,774	3,873	7,754	8,266	44,159
				Dollars			
Per family							
1990	28,472	25,916	27,629	18,096	25,335	31,916	35,206

Source: Economic Indicators of the Farm Sector, National Financial Summary, 1990, ECIFS 10-1, ERS-USDA, November 1991.

TABLE XII

Rates of Return on Farm Assets and Equity (Excluding Operator Households), 1970–1990[a]

	Rates of return on farm assets			Rates of return on farm equity		
Year	Current income	Real capital gains	Total	Current income	Real capital gains	Total
			Percentage			
1970	3.0	−0.6	2.3	2.2	0.2	2.4
1971	3.0	2.9	5.9	2.3	4.4	6.7
1972	4.2	7.5	11.7	3.7	9.8	13.6
1973	7.7	10.2	17.9	7.9	13.8	21.6
1974	4.5	−2.1	2.4	4.0	−0.9	3.1
1975	3.6	7.5	11.1	2.8	10.2	13.0
1976	2.1	9.7	11.8	1.0	12.5	13.5
1977	1.8	3.6	5.4	0.5	5.5	6.0
1978	2.4	8.5	10.9	1.2	11.7	12.9
1979	2.5	4.9	7.4	1.2	7.6	8.8
1980	1.2	−0.5	0.7	−0.6	1.3	0.7
1981	2.3	−8.0	−5.7	0.4	−8.0	−7.6
1982	2.2	−8.0	−5.8	0.0	−8.6	−8.6
1983	1.3	−2.6	−1.2	−1.1	−2.2	−3.3
1984	3.0	−12.9	−9.9	0.9	−15.4	−14.5
1985	3.6	−12.3	−8.7	1.9	−15.0	−13.1
1986	3.8	−7.6	−3.8	2.1	−9.1	−6.9
1987	4.8	2.8	7.6	3.6	4.6	8.2
1988	4.5	1.3	5.8	3.3	2.4	5.7
1989	5.5	−2.3	3.2	4.5	−1.9	2.6
1990	5.2	−2.6	2.5	4.2	−2.2	2.0

Source: Economic Indicators of the Farm Sector, National Financial Summary, 1990, ECIFS 10-1, ERS-USDA, November 1991.

[a] Rates of return are estimated using the current cost (market value) of assets and equity, not historic cost.

Vertical integration normally requires fairly large-scale operations to generate economically viable units. For example, a small-scale hog operation cannot effectively start its own feed manufacturing or meat processing facilities. Consequently, a move toward vertically integrated production is likely to bring with it a move to fewer and larger farms. These integrated units are also likely to involve more partnerships and corporate forms of business. These units are also very profit oriented and are thus unlikely to remain in low profit ventures simply to maintain a "way of life."

B. Contract Production

Closely related to vertical integration, contract production involves legal linkages between producers and either input supply or, more commonly, processing or distribution firms. Unlike vertical integration, ownership of the various stages of production remains with separate parties.

The variety of production contracts now being offered to agricultural producers is so numerous and varied that it is not easy to give a simple yet comprehensive classification scheme. However, the method of classifying contracts developed by Mighell and Jones almost 30 years ago is still quite useful.[1] They divided production contracts into three basic categories:

(1) Market-specification contracts
(2) Production-management contracts
(3) Resource-providing contracts.

The characteristics of these types of production contracts are further explained in Table XIII. Many of the contracts offered in grain and specialty crops are market-specification contracts. Contracts for vegetables and seed production tend to be oriented toward production-management contracts with some taking on the characteristics of resource-providing contracts. Contracts for livestock production tend to be resource-providing contracts or production-

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[1] Mighell, Ronald L. and Lawrence A. Jones. *Vertical Coordination in Agriculture*. Agriculture Economics Report No. 19. Washington, D.C.: Economic Research Service, USDA. 1963

TABLE XIII

Characteristics of Agricultural Production Contracts

	Types of contractual arrangements		
Characteristics	Market-specification	Production-management	Resource-providing
Involvement by contracting firm	Low	Medium	High
Level of producer's independence	High	Medium	Low
Contractor ownership of inputs or resources	None	Some	Many
Quality standard	Medium	High	High
Contracting firm's management input	Low	Medium	High
Contracting firm's ownership of final product	No	Possibly	Majority of the time
Marketing channel for producer	Guaranteed	Same	Same
Pricing of products	Fixed price specified in contract or tied to open market prices plus a premium	Fixed price is normally specified in the contract	Ownership often retained by contractor so payment is for services rendered not for the commodity
Overall producer risk	High	Medium	Low
Overall contractor risk	Low	Medium	High

Adapted from Coaldrake, K. (1992). "Contractual Arrangements in the Production of High-Value Crops in East Central Illinois: Contract Types, Producer Characteristics and Producer Attitudes." University of Illinois.

management contracts with relatively few being market-specification type contracts.

Contract production is certainly not new to agriculture. Examples of contract production abound in seed, vegetables, fruit, and broilers. Less common has been contract production in hogs, cattle, and various types of food and feed grains. However, as farms have become larger and more specialized, profit margins have narrowed. These lower profits margins on larger-scale units have left producers highly vulnerable to changes in yields and commodity prices. In response, a growing number of producers have found contract production a desirable alternative. Livestock production, especially in hogs, now appears to be headed more and more toward contract production. In contrast, feed and food grains have not yet seen dramatic increases in the use of contract production. Yet these firms face risks similar to those of livestock producers. Continued movement in the direction of contract production seems likely.

The trend toward contract production has interesting ramifications on the size and structure of farms. Farms producing under contract often face much different risks than those who operate in the open market. The primary source of risk for contracting producers is the financial stability of the integrator providing the contract. In some cases, the integrator will offer some form of loan guarantee to lenders providing loans to producers under contract. The net effect is an ability on the part of the contracting producer to undertake a larger size operation than would be the case without the contract. The use of contract production appears to have relatively minor impacts on farm organizational structure. Most farms entering into such contracts are sole proprietors. The ability to contract may generate a larger scale of operation and thereby create a stronger incentive for partnership arrangements with children or other related parties.

Production and marketing coordination are often provided through the efforts of producer cooperatives and bargaining associations. These efforts at production-marketing coordination are particularly strong in dairy, and fruit and vegetable production. Other agricultural products may become more closely linked to this process as the benefits of a coordinated production-marketing strategy become more clearly documented and demonstrated.

C. Debt vs Equity Capital

Capital used in agriculture can be broken into two major classes; debt capital provided by lenders, and equity capital provided by owners. One can further distinguish equity capital according to whether it is provided by owner-operators or whether it is provided by "external" sources. One of the emerging trends in agriculture is the growing importance of "external" equity capital for the ownership of farmland. External equity capital has been attracted to farmland in recent years for two major reasons: the high cost of borrowed funds relative to the expected returns from land, and the attractiveness of returns on farmland relative to other investment options.

Owners of farmland obtain returns from two sources, income returns and capital gains (losses). The later returns are realized only when the land is sold. Information in Table XII revealed that the income return to farm assets is relatively low. But if one owns the land and rents it out, it is not uncommon to obtain cash rents in the range of 4–6% per year. If one combines this with inflationary expectations for farmland values which are now in the range of 2–4% by most estimates, the total return to the ownership of land is expected to be 6–10% annually. However, the cost of borrowing money to buy land is in the range of 8–10% creating little economic incentive for farm operators to borrow money to buy land.

However, people who inherit land from relatives, or investors who have substantial assets to invest may find an 8–10% return relatively attractive in today's financial environment. Consequently, investment in farmland that is equity financed may appear to be a relatively sound investment. The net result of these economic circumstances should propel the farm sector toward more absentee ownership of land, and consequently a higher proportion of rented land than in the past.

D. Agricultural Trade Liberalization and Export Subsidies

The current efforts to liberalize trade is most evident in the current negotiations being conducted under the auspices of the General Agreement on Tariffs and Trade (GATT). The GATT negotiations have the goal of reducing trade distorting tariffs and subsidies on agricultural commodities. Many of the developed nations including the United States, the European Community, and Japan support agricultural prices through a complex set of tariffs, import restrictions, and export subsidies. In contrast, many developing nations use implicit or explicit export taxes to set their agricultural prices well below world market-clearing levels. The net effect is overproduction in developed countries and too little production in developing economies. [*See* TARIFFS AND TRADE.]

While GATT negotiations have encountered many roadblocks, the efforts to lower subsidies and encourage agricultural trade are clearly receiving considerable attention. To the extent that such trade liberalization policies occur, domestic producers could face stiff competition from foreign sources. Reduced price supports could result in a further loss of some of the less efficient producers and could easily speed the change in types of products which are produced.

Other examples of movements toward liberalized trade include the Canada–U.S. Trade Agreement (CUSTA) and the North American Free Trade Agreement (NAFTA) which is currently being negotiated. The impact of such trade agreements will vary by type of farm and by geographic location. However, the net effect will be to require firms to compete on a more global scale. Production activities in which the United States has a comparative advantage will flourish, while protected segments of agriculture may diminish.

V. Summary and Conclusions

Change has continually reshaped the size and structure of U.S. farms. In earlier decades, this change was driven by the availability of land as the nation expanded westward. This period entailed a rather substantial growth in the number and size of farms.

Changes in production technologies, beginning as early as the decade of the 1920s, started to alter the economics of farm production. Larger more efficient production units began to replace the smaller less efficient operations. Smaller and less efficient farms began to rely on off-farm income as a more important source of livelihood. These changes created a more dichotomous agricultural structure: large efficient farms that obtain most of their income from farming operations, and small part-time farms that obtain most of their income from off-farm sources.

The size and structure of farms will continue to change in the future. However, these changes will likely be driven by a somewhat different set of forces than existed in the past. One form of change has involved a greater linkage of the various stages of agricultural production. Continued movement toward vertically integrated and/or contract production is likely to significantly alter the structure of agriculture. Likewise, a growing commitment to liberalization of agricultural trade and the subsequent reduction of agricultural subsidies is likely to create forces for change that are linked to a global economy. On balance, it appears that these emerging trends will create an economic climate conducive to fewer, larger, and more efficient farming operations. At the same time, these forces should continue to generate an abundant supply of food at reasonable prices.

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V

Viticulture

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Glossary

Bearing wood Sections of cane possessing the buds that produce the fruit-bearing shoots

Cane Mature portion of a shoot

Cordon Branches from the grapevine trunk, usually horizontally positioned

Coulure Physiological disorder showing excessive fruit drop shortly after pollination

Inflorescence Flower cluster and associated supporting structures

Isotherm (annual) Line connecting locations on a map possessing the same average yearly temperature

Rootstock Cultivar to which most commercial grapevine varieties are grafted to provide the root system

Scion Shoot- and fruit-bearing portion of a grafted grapevine

Training system Form of the shoot system developed to position the fruit for optimal fruit yield and quality

Véraison Period when the fruit begins to lose its green coloration and commences its last growth phase

Viticulture deals with the cultivation of wine, table, and raisin grapes. Because each use involves its own set of desirable fruit characteristics, it is uncommon for individual cultivars to be grown for more than one purpose. Vineyard climate and soil characteristics impose limits on cultivar suitability, as much as cultivar choice places limits on site appropriateness. Viticultural practices that can influence cultivar–site compatibility involve training system and rootstock use as well as the type and degree of fertilization, irrigation, and disease/pest management. Harvest method and timing depend primarily on cultivar characteristics and grape use.

I. Introduction

When and where humans first began to cultivate grapes will probably never be known. Absence of a common root word for grape in Indo-European languages suggests that the discovery of grape edibility occurred independently throughout Europe. The ancestral range of the European grape (*Vitis vinifera*) extended around the Mediterranean coast, westward from Algeria around to Syria, up into central Europe, and east to between the Black and Caspian seas. Most researchers believe that the origin of viticulture occurred within the Anatolian region of northern Turkey or adjacent Transcaucasia. This zone includes the regions in which the distribution of wild *V. vinifera* grapevines most closely approaches the origins of Western agriculture in the Near East.

Current evidence suggests that grapes and viticulture were introduced to Palestine and Egypt from the Caucasus about 4000 B.C. Beginning about 1000 B.C., grape culture spread throughout most of the Mediterranean Basin; spread continued into central Europe during the Roman period. Viticulture subsequently spread into Asia and finally throughout much of the world in the past few centuries.

Most commercial viticulture is restricted to regions located between the 10 and 20°C annual isotherms in the Northern and Southern Hemispheres. Where local conditions or vineyard practices compensate, viticulture is possible in warmer subtropical regions and in colder temperate zones. In moist subtropical regions, disease problems become increasingly limiting and severe pruning is required to promote bud burst for continued growth. In cold regions, winter survival may require the whole shoot system to be laid on the ground for burial each fall.

II. Economic Importance

Grapes are the world's most important fleshy fruit crop. Global production in 1992 was about 60.6 million metric tons. In comparison, global production of oranges, bananas, and apples, according to data from the United Nations Food and Agriculture Organization (FAO), was 57, 49.6, and 43.1 million metric tons, respectively. Although viticulture has spread around the globe, the main centers of grape culture remain in Mediterranean Europe (Tables I and II). About 68% of the world's vineyard hectarage occurs in Europe, of which 40% of the world total is located in Spain, Italy, and France. Global grape usage varies considerably from region to region and country to country (Tables I and II). For example, most French grapes are used in wine production whereas most Turkish grapes are grown for raisin production or for use as a fresh fruit crop.

III. Grape Species and Cultivars

The most important grapevine species is *V. vinifera*, the dominant or only grapevine species grown in most of the world, with the exception of the Pacific northwestern and eastern regions of North America, Brazil, Uruguay, Japan, and northern China. In the latter regions, most vines are cultivars of or hybrids between two or more North American *Vitis* species (American hybrids) or complex hybrids between North American species and *V. vinifera* (French–American hybrids). In American hybrids, the primary species involved are *V. labrusca*, *V. aestivalis*, *V. riparia*, and *V. cinerea*, whereas in French–American hybrids the main North American species are *V. rupestris*, *V. riparia*, and *V. aestivalis*. The latter species were used as sources of disease and pest resistance. Several newer *V. vinifera* hybrids are being produced using *V. amurensis* from Manchuria to provide cold tolerance, and using several species native to the southern United States, Mexico, Central America, and southern China to enhance adaptation to warm humid climates. In the southeastern regions of the United States, most cultivars are derivatives of *V. rotundifolia*, the muscadine grape.

North American *Vitis* species have been used almost exclusively in the development of rootstocks for grafting *V. vinifera* cultivars. Rootstocks can (1) provide resistance or tolerance to various root pests, including phylloxera and nematodes, as well as to several soilborne viral pathogens; (2) donate increased tolerance to high-calcium soils, salt, and drought; and (3) regulate vegetative vigor. Grapevines in most commercial viticultural regions must be grafted onto appropriate rootstocks.

There are about 15,000 named grape varieties, most of which are wine grapes, reflecting the major use of the fruit. The most widely grown cultivars are a few varieties grown extensively in Spain, the former Soviet Union, and South America. Because wines from these cultivars are rarely seen in world channels, and typically do not carry a varietal designation, the names

TABLE I

World Regional Statistics for Vineyard Coverage and Total Grape, Wine, Table Grape, and Raisin Production in 1992[a]

	Vineyard area		Total grape production		Wine production		Table grapes		Raisins	
Region	10^3 ha	%	10^6 kg	%	10^6 liter	%	10^6 kg	%	10^6 kg	%
Africa	351	4.2	2732	4.5	1148	3.8	649	7.8	46	4.5
Americas	784	9.5	10,278	17.0	4064	13.5	1664	20.0	338	32.6
Asia	1407	17.1	9402	15.5	483	1.6	1782	21.4	489	47.2
Europe	5626	68.3	37.132	61.3	23,857	79.4	4142	49.7	81	7.8
Oceania	67	0.8	1041	1.7	500	1.7	94	1.1	82	7.9
Total	8235		60,585		30,050		8330		1036	

[a] Data from Tinlot and Rousseau (1993). The state of vitiviniculture in the world and the statistical information in 1992. *Bulletin de l'Office Internationale de la Vigne et du Vin* **66,** 861–943.

TABLE II

Top 10 Countries in Vineyard Coverage and Total Grape, Wine, Table Grape, and Raisin Production in 1992[a]

	Vineyard area			Total grape production			Wine production			Table grapes			Raisins	
Country	10^3 ha	%	Country	10^6 kg	%	Country	10^6 liter	%	Country	10^6 kg	%	Country	10^6 kg	%
Spain	1360	16.5	Italy	10,178	16.8	Italy	6869	22.8	Italy	1766	22.2	Turkey	350	33.8
Italy	1008	12.2	France	8514	14.1	France	6540	21.8	USSR (ex)	1012	12.1	United States	298	28.7
France	950	11.5	United States	5490	9.1	Spain	3704	12.3	Turkey	921	11.1	Australia	82	7.9
USSR (ex)	813	9.9	Spain	5356	8.8	USSR (ex)	1800	6.0	Chili	689	8.3	Greece	78	7.5
Turkey	580	7.0	USSR (ex)	4545	7.5	United States	1562	5.2	United States	572	6.9	Iran	55	5.3
Portugal	371	4.5	Turkey	3450	5.7	Argentina	1435	4.8	Spain	407	4.9	Afghanistan	45	4.4
United States	301	3.7	Argentina	2127	3.5	Germany	1340	4.5	Brazil	261	3.1	South Africa	44	4.2
Romania	252	3.1	Germany	1735	2.9	South Africa	1000	3.3	Algeria	257	3.1	Chile	17	1.6
Iran	232	2.8	Iran	1650	2.7	Portugal	755	2.5	Japan	252	3.0	Mexico	17	1.6
Argentina	209	2.5	South Africa	1406	2.3	Romania	750	2.5	Greece	206	2.4	Syria	15	1.4

[a] Data from Tinlot and Rousseau (1993). The state of vitiviniculture in the world and the statistical information in 1992. *Bulletin de l'Office Internationale de la Vigne et du Vir* **66,** 861–943.

of these cultivars are unfamiliar to most wine consumers. Examples are Airen, Rkátsiteli, Trebbiano, Garnacha, Carignan, and País (Criolla). In contrast, most well-known grapevine cultivars constitute only a small fraction of the vines grown, even in the country of origin. The comparatively small vineyard area given over to famous cultivars partially reflects the more demanding conditions required to develop their unique varietal character. Some of the most highly prized wine cultivars are Cabernet Sauvignon, Chardonnay, Pinot noir, Riesling and Syrah (Shiraz).

For wine grapes, it is desirable to have relatively small berries, providing a high skin-surface to juice-volume ratio. The skin and the immediately underlying tissues possess the pigments of red grapes and most varietally distinctive aroma compounds. It is also preferable that the internal tissues of the fruit hydrolyze during ripening. This process greatly eases juice extraction and limits the development of pectin-induced cloudiness in wine. High sugar contents (22–25%) and comparatively acidic juice (pH 3.1–3.5, 0.55–0.85 g/liter titratable acidity) are desirable at maturity. Better cultivars possess a distinctive subtle aroma sufficient to generate but not mask the development of a complex wine fragrance.

Table grapes are thought to be the most ancient of grapevine cultivars because of their extensive accumulation of mutations. Most table grape varieties are unpigmented (produce no anthocyanins), partially to completely seedless, large fruited, low in acidity (0.3–0.6 g/liter), and moderate in sugar accumulation (18–20%). Additional desirable traits include retention of a pulpy flesh and the ability to be stored for several months (to extend the shipping period of the crop). Most long-established table grape varieties are thought to have originated in central Asia or the Near East, and are adapted to hot arid climates. Several hundred table grape varieties are grown worldwide. Some of the more important cultivars are Almeria, Calmeria, Dattier, Emperor, Malaga, Perlette, Ribier (Alphonse Lavallée), Flame Tokay, and Thompson Seedless (Sultana).

Theoretically, any cultivar can be used for raisin production; in practice, only a few are. Thompson Seedless (Sultana) is the most extensively used cultivar in almost every raisin-producing region of the globe. However, Muscat of Alexandria is the dominant raisin cultivar in a few countries. For currant production, Black Corinth (Zante Currant) is grown almost exclusively.

IV. Yearly Growth Cycle

Initiation of grapevine growth in the spring commences when conditions permit sufficient physiological activity for the sap to flow. This occurs when temperatures warm, vine cells have lost their cold acclimation, and exposure to cold has reversed bud dormancy. The impending reactivation often is indicated by sap bleeding from the cut ends of last year's growth. The rate of bud swelling and cell growth depends on the ambient temperature. Although this is a varietal trait, most cultivars show rapid resumption of growth when the average daily temperature reaches about 10°C.

Reactivation of growth tends to begin in the most terminal buds and to progress downward. Reactivation initially involves the dissolution of the callose inclusions that plug the sieve cells in the fall. Subsequently, the vascular cambium becomes active, producing new xylem and phloem cells internal and external to the cambium, respectively.

As buds swell, cells in the primary (main) bud of the overwintering compound bud begin to grow and divide. The elongating embryonic shoot and enlarging leaves force the bud scales apart. The two embryonic inflorescences typically found in each fertile (flower-bearing) bud also recommence their development. The other two buds (secondary and tertiary) of the overwintering bud usually remain inactive. Only when the primary bud is killed or severely damaged does the secondary bud become active. Tertiary buds may develop and burst if both primary and secondary buds are killed.

Once reactivated, shoot growth rapidly reaches its maximum within a few weeks. Subsequently, shoot growth slows and essentially stops about 100 days after bud burst. Unlike most temperate perennial plants, grapevines do not show determinate growth, that is, the formation of terminal dormant buds at the shoot apex. If considerable vegetative growth occurs throughout the summer, it typically results from lateral bud activation. All leaves produce compound buds at the leaf base, where the petiole joins the shoot (axil). The newly formed compound bud possesses four buds, the outermost and most mature of which is called the lateral bud. If the lateral bud becomes active and produces a shoot (called a lateral), the bud does so in the season of its production. The inner three buds (primary, secondary, and tertiary) remain dormant, and potentially become active only in subsequent years. Compound buds formed in the leaf axils of lateral shoots may become active and produce a third set of vegetative shoots in a single season. Each shoot system has the potential to produce its own fruit crop.

The potential of grapevines to produce three shoot systems in any one season provides the plant with an incredible ability to adjust to changing environmental conditions and stresses. Limiting this vegetative potential is one of the major tasks of the grape grower. The energy of the vine needs to be shifted from continued vegetative growth toward increased production of fully ripened fruit, preparing the plant for winter, and sustaining long-term vine health. Excessive vegetative growth draws nutrients away from developing buds and produces shading that reduces inflorescence initiation for the subsequent season's crop. Continued shoot and leaf production also limits nutrient availability for berry development. In addition, late vegetative growth and shading retard bud and cane maturation, and can result in increased winter injury. Finally, because most shoot growth is removed (pruned) at the end of the season, excessive shoot production can result in the associated loss of considerable stored nutrients and can retard subsequent canopy production.

The initiation of significant root growth in the spring usually starts when shoot growth has begun to slow. Root extension usually reaches its maximum and starts to decline between flowering and the last phase of berry development. In some regions, a second root growth period occurs in the fall.

As the shoot extends and the leaves unfold, the embryonic inflorescences begin to elongate and the flowers mature. Typically, two inflorescences are produced per shoot, located opposite the third and fourth, fourth and fifth, or fifth and sixth leaves. Flowering generally occurs when the average daily temperature approaches 20°C. Self-pollination usually results when the fused petals (calyptra) separate from the base of the flower, shaking pollen from the anthers onto the stigma. Warm sunny conditions encourage the rapid flowering and fertilization that promote uniform fruit ripening. Pollination is essential for fruit initiation, even in "seedless" varieties. In seeded cultivars, the number of seeds per berry (maximum 4) influences the size of the fruit. Typically, one fertilized seed per berry is necessary to produce the hormones required to maintain fruit development. Dehiscence of fruit with few or no fertile seeds (shatter) occurs shortly after flowering. The sensitivity of some cultivars to excessive shatter is called *coulure*. In seedless varieties, timing of seed abortion influences the maximum size of the fruit. Spraying with natural or artificial plant hormones can compensate for a deficiency and promote increased fruit size.

Induction of the two inflorescences typically found in fertile buds for the subsequent year's fruit production is separated by several weeks. The induction and initial differentiation of their development typically occur, respectively, during blooming and the initial phase of fruit enlargement of the current year's crop.

Berry development is commonly divided into four phases. Phase I refers to the initial growth period during which most cell division occurs. Phase II is a less well defined period during which fruit enlargement is minimal and most seed development occurs. Phase III is the second berry growth period, when most increase in fruit size results from cell enlargement, especially in the flesh. The initiation of Phase III is termed *véraison*. From this point onward, the berry begins to take on its mature coloration and shows marked sugar accumulation, its acidity declines, and varietal flavors are generated. Transport of water and inorganic nutrients from the xylem and subsequently water, inorganic, and organic nutrients from the phloem eventually ceases. By the end of Phase III, all vascular connections with the fruit are broken or sealed. In Phase IV, postmaturation changes include continued fruit softening and acidity decline, degradation or modification of aromatic compounds, and progressive drying.

Because climate and soil conditions can significantly influence grapevine growth and berry maturation, most vineyard activities are designed to diminish undesirable effects and promote favorable influences. Assuming that water, nutrient, pest, and pathogen stresses are adequately controlled, the primary factors affecting fruit ripening are the solar and temperature conditions around the vine and fruit. In cooler regions, maximal exposure of the fruit to the sun is usually preferred, whereas in hot arid climates, some shading of the fruit is usually beneficial.

Solar radiation has both direct and indirect effects on berry development. Because berry photosynthesis is limited and occurs only during the pre-*véraison* periods, the primary direct effect of sun exposure is through its greater proportion of red and ultraviolet radiation. In contrast, shade light has a higher proportion of blue wavelengths, because of the absorption of red and ultraviolet radiation by the leaf canopy, and the blue enrichment of skylight. The higher proportion of red radiation in direct-beam sunlight can enhance the activation of certain enzymes such as those promoting malic acid respiration. Direct sun exposure is also important in the development of mature berry coloration, aroma development, and sugar accumulation. Ultraviolet radiation favors cuticular development of the fruit and leaves, and thus tends to reduce disease incidence. Indirectly, solar radiation causes fruit heating and enhances the rate and extent of the decline in fruit acidity. In addition, heating enhances transpiration and the accumulation of nutrients transported in the xylem and phloem. Sun and wind exposure also speed the drying of fruit and leaf surfaces, thus limiting infection by a wide range of pathogens.

V. Vineyard Site Selection

Selection of a vineyard site and appropriate cultivars involves both site–cultivar compatibility and anticipated financial returns. The most widely used indicator of site–cultivar suitability is the heat summation (degree–day) system developed by Winkler and Amerine for California. In most locations, however, heat summation data must be complemented with relevant soil and vineyard climate details. Important modifying meso- and microclimatic conditions include factors such as minimum winter temperatures, frequency of early fall and late spring frosts, relative humidity, solar exposure, and soil drainage. The more closely regional conditions approach the limits of a proposed cultivar's climatic suitability, the more significant become the meso- and microclimatic factors of the site. For example, sloped vineyard sites become progressively more valuable the higher the latitude. Slopes can increase solar exposure, especially valuable in the spring and fall; can enhance drainage, permitting earlier soil warming and vine activation; and can direct cool air away from the vines, potentially extending the frost-free growing season by several weeks. A porous rocky soil can be valuable in rapid soil warming during the day and heat radiation to the vines during the night. Dark soils can further increase the absorption of solar radiation and moderate the microclimate around the vines.

In dry climates, where irrigation water is unavailable or prohibited, deep soils may permit grape culture by letting roots reach deep sources of groundwater. In certain regions such as the sherry region of Spain, development of a hard, noncracking, chalk crust in the summer can limit water evaporation from the soil. Soil texture can also significantly influence the upward capillary movement of water in the soil, supplying surface roots with moisture under dry conditions.

VI. Vineyard Establishment

Establishment of a vineyard involves even more capital investment than is usually required to start an orchard of equivalent size. In comparison, however, fruit production approaches typical values sooner in vineyards. Commercial production is often reached within 4–5 yr on fertile soils, whereas on drier low-nutrient hillside sites standard yields may not be reached for 6–7 yr. No crop is produced for the first 3 yr and production is usually prevented by inflorescence removal until the fourth year. The first 3-yr growth is directed to establishing the grapevine's woody structures and initiating its training system.

The planting of new vineyards, or the insertion of replacement vines, normally involves the use of grafted cuttings. Young vines are obtained by grafting short cane sections or buds from the desired scion variety onto a rootstock possessing appropriate resistance and agronomic traits. Choosing the appropriate rootstock or combination of rootstocks for a vineyard is crucial, since an error at this point may require uprooting and replanting years in advance of the usual productive life-span of a grapevine (40–50 yr).

Rootstock canes may be induced to root before or after grafting the scion, depending on the ease with which rooting occurs. All buds are removed from the rootstock cane before grafting the scion. It is important that the cambial tissues of the scion and rootstock be contiguous and protected from drying. In several countries, grafted vines are produced by specialist nurseries and are purchased on contract for direct planting in the vineyard.

The type and degree of preparatory vineyard work depends on whether the location is virgin land or has been previously cultivated. For a new vineyard, deep tilling may be essential to ensure good drainage. Depending on whether irrigation is necessary, and the type to be installed, laying pipes or ground leveling may be necessary, and is preferably performed before planting. If the field is contaminated with noxious weeds, nematodes, or other soil-inhabiting pests, use of eradicative herbicides or soil sterilization is easier and safer before planting.

In planting, it is crucial to provide adequate water to promote early root system development and to ease root penetration into the surrounding soil. Soil penetration is further facilitated if the hole has loose, uneven, angled sides and is backfilled with soil of the same type and texture as the vineyard. Both features reduce the likelihood of root growth being confined within the planting hole. Plastic mulches are useful in promoting early and extensive root growth as well as controlling weed growth around the young grapevines.

During the first season, vegetative growth is permitted to develop essentially at will. Watering usually is stopped after the end of July to slow vegetative growth and to promote cane maturation. In late fall or winter, after leaf drop, the vine may be pruned back to the strongest shoot. The latter is tied upright to a stake to become the trunk of the developing grapevine. This cane may be pruned back to the four most mature buds. During the second year, pruning is conducted consistent with the training system desired. The third year's growth further establishes the training system and initiates the inflorescences for the subsequent year's crop. Grapevine productivity usually reaches its maximum within 7–10 yr.

VII. Training Systems and Pruning

Probably several hundred named training systems exist worldwide, with new forms continually being developed and older systems being refined. Each system attempts to direct most of the vine's energy into producing mature fruit and maintaining the long-term health of the vine. Most systems have developed in particular regions in response to the prevailing climate and soil conditions and the needs of local grape cultivars. Newer systems such as the Geneva Double Curtain (GDC), Lyre (U), Ruakura Twin Two Tier (RT2T), and Scott Henry Trellis (SH) are divided-canopy systems. In other words, the shoots coming from a variously branched cordon system are positioned to minimize leaf and fruit shading. Thus, the training system provides conditions that can direct the potentially excessive vigor of strong, healthy vines into increased yield and improved fruit quality. Vines freed from systemic viral and bacterial pathogens, on moist fertile soil, with weed, fungal, and other pest problems adequately regulated tend to be excessively vigorous when traditional training systems are employed. The latter often were developed for vines unknowingly infested with several systemic pathogens and were cultivated on relatively poor soils under dryland conditions. These conditions, associated with severe pruning, restricted vine growth and promoted fruit maturity.

Canopy division physically separates and directs the larger number of primary shoots adequately supported by strong vines to maximize solar exposure. The increased number of grape clusters produced places an early nutrient drain on the vine, limiting the activation of lateral shoots. Physical placement of the shoots over a wide area minimizes canopy and fruit shading. Limited shading and a more open canopy speed drying of the foliage and fruit, help minimize disease incidence, and facilitate the application of chemical sprays if required.

Training systems are often classified relative to the length of the bearing wood retained at the end of the growing season. Short canes with two to four buds are called spurs, whereas longer sections possessing upward of 12 buds are termed canes. Most training systems also may be grouped as head trained, with bearing wood arising from a central crown (head), or cordon trained, with bearing wood located along one or more branches of the trunk (cordons). Training systems also may be grouped based on shoot positioning (vertically upright or downward, pendulous, or horizontal), canopy height (low, standard, or high), or trunk number. Several trunks may be developed per vine when the incidence of crown gall is high.

An old but expensive system of regulating vine vigor, still popular in some parts of Europe, is high density planting. This method involves some 4000–5000 vines/ha, in contrast to the 1100 to 1600 vines/ha common outside Europe. High density planting limits root extension, while promoting early grapevine productivity, increased yield per hectare, and full fruit maturation. Modern divided-canopy systems achieve many of the same goals (increased yield of high quality fruit) at lower initial costs. Purchasing grafted vines is one of the major expenses of establishing a vineyard. Modern training systems also use wide row spacing, and thus are compatible with most currently used vineyard equipment in the New World.

Because of shifts in consumer demand, it may be desirable to convert some or all of an existing vineyard to another variety. Grafting over is much less expensive and more rapid than tearing out the existing vines and replanting. In grafting over, the head of the grapevine is removed and several canes or buds of the desired scion variety are grafted onto the trunk. The shoots derived from the grafted scion are trained into the new fruiting portion of the vine. Nearly full productivity may be reestablished within about 2 yr. [*See* PLANT PROPAGATION.]

Between leaf fall and the start of growth in the spring, most of the shoot growth (~90%) is pruned away. Pruning has several purposes. One of the primary functions is to regulate fruit production by removing excess fertile buds. Thus, depending on the capacity of the vine, a cultivar-specific number of buds is retained. By judicious selection of the bearing wood, the grape grower can both direct the initial growth of the shoots and choose their position on the vine. Both features are important in providing the shoots with the best solar exposure for growth and fruit ripening. Pruning is also essential to maintaining the training system.

In the majority of training systems, it is important to neither overprune nor underprune. Overpruning tends to promote lateral bud activation, berry shading, and delayed fruit ripening. Underpruning can result in excessive fruit production, delayed maturation, and poor berry quality. In a few years, however, unpruned vines may adjust by producing smaller grape clusters on thin shoots, whose extremities self-dehisce. Consequently, fruit quality improves to the point where it approximates that of many of the better training systems. This observation has led to the development of the minimal-pruning training system. In minimal pruning, the vine is initially trained to a bilateral cordon, after which pruning is primarily limited to skirting (the removal of shoots that trail down to the ground). Minimal pruning provides considerable cost savings while producing increased yields of good quality fruit that is easily harvested mechanically. Minimal pruning has proven popular in many of the drier regions of Australia.

Most pruning is conducted in the late fall or winter months, because choosing the cane wood and counting the number of buds to retain is easier when the vine is defoliated. However, in some situations additional summer pruning is desirable. Removing various lengths of shoot growth is termed trimming. Trimming the terminal few centimeters of the growing shoots during flowering can enhance fruit set in varieties sensitive to *coulure*. Later removal of longer shoot segments may be employed in windy climates to produce more sturdy shoots, to limit excessive leaf and fruit shading, or to ease movement of machinery through the vineyard. However, trimming must be done judiciously since it can induce lateral bud activation, producing a carbohydrate drain that can retard fruit ripening and cane maturation.

Other forms of summer pruning include flower- and fruit-cluster thinning. These procedures may be used to limit yield when more fertile buds survive the winter than expected. In cold climatic regions it is usual to leave more buds than "ideal," in the expectation that a portion will not survive the winter.

An increasingly popular summer pruning technique is basal leaf removal, which involves removing the leaves adjacent to, and immediately above and below, fruit clusters. This method improves the light and humidity microclimate around the berry cluster, and thus promotes fruit quality and health. Basal leaf removal also permits the more efficient application of pest control chemicals.

VIII. Fertilization

Grapevines are one of the few major crops with modest yearly nutrient demands. This characteristic partially explains why viticulture historically could be relegated to poor hillside soils, or vines trained up trees on the edges of fields and roadsides. The deeply penetrating root system of grapevines allowed them to gain access to water and nutrients beyond the reach of annual food crops.

The potential of the vine to obtain nutrients deep in the soil, and the extensive storage of nutrients in the woody structures of the vine, severely complicates assessing the value of most fertilizer applications. This problem is important since excess fertilization is economically wasteful, can lead to groundwater pollution, and can disrupt the uptake of other nutrients. For example, grapes are seldom deficient in phosphorus and its addition can interfere with potassium uptake. Although most inorganic nutrients are nontoxic at higher than typical soil concentrations, increasing the availability of several micronutrients such as boron and zinc rapidly leads to toxicity.

Many factors affect nutrient availability and uptake by the vine, most of which are not readily influenced by the grape grower. Where the soil is relatively low in organic content, adjustment of the pH upward or downward may be achieved by the addition of crushed limestone or elemental sulfur, respectively. Alternatively, rootstocks able to derive the requisite inorganic nutrients from acidic or alkaline soil may be employed.

Where soils are deficient in particular nutrients, optimal application requires their addition at appropriate rates and times, and in appropriate manners. For example, addition of ammonia should be conducted sufficiently in advance of peak nitrogen-demand by the grapevine, providing time for soil bacteria to convert the ammonia nitrogen into the more readily absorbed and mobile nitrate form. Because most positively charged mineral nutrients such as potassium do not migrate effectively through the soil, it is important for effective uptake that they be applied throughout the root zone. For micronutrients, deficiency often can be treated by foliar application.

After being out of favor for many years, the use of manures has received renewed interest. In addition to the slow release of inorganic nutrients, manures liberate organic chelators that help retain inorganic nutrients in readily available forms. Chelators and other humic components of manure also promote the development and maintenance of the soil's aggregate structure and friability. The latter features improve soil porosity, facilitating water and air penetration, and minimize soil erosion.

IX. Irrigation

In some regions, notably Europe, irrigation is prohibited for wine grapes. Although excessive irrigation can result in increased yield and reduced fruit quality, proper application can regulate vine vigor and promote fruit ripening and quality. In addition, in many semiarid and arid regions, viticulture would not be commercially viable without irrigation.

Grapevines are particularly sensitive to water stress in the first few weeks following flowering. Water stress during this period can result in permanent restriction in maximum fruit size. Although normally undesirable, restricting berry enlargement by limiting water availability has occasionally been done to avoid fruit-cluster compactness and to diminish the incidence of Botrytis bunch rot. Early water stress also can negatively affect inflorescence induction and fruit set. After *véraison*, limited water deficit can be beneficial in restricting additional vegetative growth, promoting cane maturation, and enhancing berry ripening. When water deficiency develops slowly, the vine often temporarily counteracts its effects by increasing root growth, decreasing root osmotic potential (to favor water uptake), and modifying stomatal response (to reduce water loss by transpiration).

Because the physiological effects of water stress may last for several days following the restoration of turgor, prediction of the development of a water deficit is important in timing irrigation. Recently, the use of hand-held infrared thermometers has become popular in assessing impending water stress. As water stress develops, stomatal closure results in a sharp rise in leaf temperature above ambient temperature, as the cooling effect of transpiration decreases.

Three main irrigation techniques are used in viticulture: furrow, sprinkler, and drip systems. Their respective use depends partially on the cost, availability, and quality of the water, and on installation cost, vineyard topography, and auxiliary uses. [*See* IRRIGATION ENGINEERING: FARM PRACTICES, METHODS, AND SYSTEMS; WATER: CONTROL AND USE.]

Where water is inexpensive and of ample supply, the relatively inefficient use of water by furrow irrigation may not be an important factor. Furrow irrigation has the lowest installation cost of any irrigation system, but is applicable only on relatively level terrain. Care must be used on heavy soils, where disruption of soil aggregate structure results in clay particle migration, plugging of soil pores, and decreasing infiltration rates.

In cooler regions, where protection from late-spring or early-fall frosts is frequently necessary, sprinkler irrigation has a distinct advantage. Under frost conditions, the release of heat as irrigation water freezes on the vine limits the formation of ice crystals in plant tissues. Sprinkling must be continued until atmospheric conditions warm sufficiently to melt the ice coating. Otherwise, heat to melt the ice is extracted from vine tissues and frost damage can develop. Sprinkler irrigation has less tendency to disrupt the soil's aggregate structure because nozzle opening and application rates can be chosen to limit soil puddling. When the salt content of the water is higher than ideal, irrigation may need to be limited to evenings or cloudy days to minimize toxic salt build-up on the fruit and foliage due to evaporation.

Although sprinkler irrigation is suitable for sloped terrain, drip irrigation is often preferred. Drip irrigation has many advantages including maximal efficiency of water use, opportunity to apply fertilizer and nematicides jointly, avoidance of erosion and soil compaction, restricted growth of all but drought-tolerant weeds, and applicability on shallow soils or terrain where saline water is close to the soil surface. However, because root production occurs predominantly around the emitters, water stress can develop rapidly if water is not applied frequently.

X. Pest Control

Two trends are currently changing established means of disease, pest, and weed control. One is organic viticulture, in which use of synthetic chemicals is restricted or prohibited. The other trend is integrated pest management (IPM), in which control measures for all diseases, pests, and weeds of a crop are integrated and coordinated. [*See* INTEGRATED PEST MANAGEMENT.]

In organic viticulture, several grape pests can be adequately controlled by predatory or parasitic agents, but their use often requires maintaining overwintering sites for the biological control agent(s). However, control of other pests and pathogens often requires elemental or inorganic chemical pesticides such as sulfur or copper sulfate, respectively; organic chemicals such as soaps and oils; or biologically generated toxins such as that produced by the bacterium *Bacillus thuringiensis*. Use of organic fertilizers such as manure can indirectly aid disease and pest control by slowing nutrient release to the vine and minimizing the production of succulent tissues favored by most pests and pathogens.

IPM has become increasingly popular as a means of preserving and increasing the effectiveness of chemical control measures in the face of growing pest and pathogen resistance, and opposition to pesticide use by environmentalists and governments. IPM may employ all the methods used in organic viticulture but does not exclude the use of synthetic control agents.

Viticulture provides one of the oldest and best examples of biological control, the use of resistant rootstocks in regulating the ravages of the phylloxera root louse (*Daktulosphaira vitifoliae*). Without grafting to a resistant rootstock, culture of *V. vinifera* varieties would be essentially impossible in most parts of the world. Although biological controls have proven less applicable in the control of fungal, bacterial, viral, and weed problems, detailed knowledge of the biology of these agents can increase the efficiency and reduce the number of applications of chemical control agents. [*See* PEST MANAGEMENT, BIOLOGICAL CONTROL.]

Breeding was used most extensively in the late 1800s to incorporate resistance to various pests and diseases, and gave rise to the French–American hybrids. However, changes in fruit flavor limited their acceptance, especially in Europe, where laws have been passed to restrict or prohibit their cultivation. Thus, developing new resistant varieties is not a priority item in most countries, although rootstock development continues, since they do not alter the flavor characteristics of the scion cultivar.

Cultural controls include factors such as minimizing dusty conditions for spider mite control, basal leaf removal for limiting Botrytis bunch rot, and appropriate timing of suitable levels of ammonia fertilizer to reduce the production of sensitive succulent tissues. [*See* PEST MANAGEMENT, CULTURAL CONTROL.]

The efficiency of chemical control agents can be increased by the application of several new concepts and technical advances. These include avoiding the mixing of incompatible compounds, preferential use of nonspecific chemical agents (to which pest resistance develops slowly), restricted use of curative agents (to which resistance may develop quickly), alternate use of different chemical agents (to limit specific pesticide/fungicide build-up and reduce the likelihood of resistance development), use of climatic conditions in disease forecasting (to minimize unnecessary chemical applications), and use of nozzles with an appropriately narrow range of droplet sizes (to reduce drift and improve effective impact and surface coverage). [*See* PEST MANAGEMENT, CHEMICAL CONTROL.]

The incidence and importance of particular diseases and pests varies from year to year and region to region. For example, downy mildew (*Plasmopara viticola*) is a minor problem in much of California, but a major pathogen in the more humid parts of North America and most of Europe. In contrast, powdery mildew (*Uncinula necator*) and Botrytis bunch rot (*Botrytis cinerea*) are important pathogens in almost every viticultural region. Powdery mildew often is more serious in drier years, whereas bunch rot is especially prominent during wet years.

Most viral diseases such as fanleaf degeneration and leafroll are globally serious problems. Their almost universal distribution may be due to the widespread dispersal of unknowingly infected rootstock in the control of phylloxera. The most widely dispersed of bacterial grapevine pathogens is *Agrobacterium tumefaciens*, the causal agent of crown gall. This pathogen is particularly damaging in cool climatic regions.

The major roundworm pathogens of grapevines are the root-knot nematodes (*Meloidogyne* spp.) and dagger nematodes (*Xiphinema* spp.). The latter are important vectors of the grapevine fanleaf virus. Major insect pests include several types of leafhoppers and various tortricid moths (e.g., several grape berry moths, the omnivorous leafroll, and the orange tortrix). Several spider mites also can cause considerable damage.

The major air pollutant causing serious grapevine damage is ozone. Severe physiological disorders in certain regions, and with particular cultivars, are *coulure* (inflorescence necrosis) and *dessèchement de la rafle* (bunch-stem necrosis). The most notable nutrient deficiency syndrome, especially on calcareous (alkaline) soils, is iron chlorosis.

XI. Harvesting

Selecting the harvest date is one of the most critical decisions in the viticultural calendar. This choice establishes the maximum quality of the fruit and the wine potentially made from it. Correspondingly, there is much concern in correctly predicting the optimal date of fruit maturity. Before the availability of analytical chemical indicators, color, texture, and taste were the only means of assessing grape ripeness. Currently, measurement of the sugar content or the sugar–acid ratio is the primary means by which grape maturity is assessed and the projected harvest date set.

For wine grapes, additional indicators of maturity may include the measurement of selected phenolic compounds such as anthocyanins, or aroma constituents and their precursors. The more the chemical nature of a grape's varietal aroma is known, the more useful its measurement may become in determining the optimal harvest date for wine grapes. Where permitted, adjustment of the sugar and acid content of the juice or wine is easier, and meets with more consumer acceptance, than artificial adjustment of the aroma. Aroma adjustment is permissible only in selected fortified wines (e.g., vermouth or marsala) or in wine-based beverages such as wine coolers. Examples of grape components potentially or actually being used in determining grape harvest are monoterpenes, methoxypyrazines, and norisoprenoid precursors.

Choice between manual and mechanical harvesting often depends as much on grape use, variety, and training system as on labor cost and availability. Topography, notably steep slopes, or vineyard layout, such as narrow rows, may require manual harvesting. In addition, use as table grapes or in the production of certain wines (white sparkling wines from red grapes) essentially makes manual harvesting obligatory. Where other conditions permit, varietal suitability and training system are the main nonmonetary factors affecting the choice of manual versus mechanical harvesting. Varietal suitability for mechanical harvesting depends on the ease with which individual grapes or clusters separate from the vine, and the resistance of the skin to rupture during separation. The fruit clusters of cultivars such as Cabernet Sauvignon and Flora separate easily, with little fruit rupture, whereas the clusters of other varieties such as Zinfandel and Muscat Canelli separate with difficulty and show medium to heavy juice release.

Where applicable, mechanical harvesting has several distinct benefits, notably picking speed and continuous operation under most climatic conditions. With cultivars suitable for mechanical harvesting, differentiation is rarely possible between wines made from grapes harvested mechanically or manually from similar vines.

Harvesting machines usually detach the fruit by shaking the vine trunk, by striking the shoots, or by a combination of both actions. Their effectiveness depends primarily on the training system and on how close or distant the fruit is from the trunk. Shaker types are generally better with spur pruned vines, whereas striker types are more effective with cane pruned vines.

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W

Waste Management Engineering

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Glossary

Aeration Process forcing intimate contact between air and a liquid by one or more of the following methods: spraying the liquid in the air, bubbling air through the liquid, and agitating the liquid to promote absorption of oxygen through the air–liquid interface

Agricultural wastes Wastes normally associated with the production and processing of food and fiber on farms, feedlots, ranches, ranges, and forests that may include animal manure, crop residues, and dead animals; also agricultural chemicals and their residues and containers, which may contribute contaminants to surface and subsurface water

Biochemical oxygen demand (BOD) Quantity of oxygen used in the biochemical oxidation of organic matter in a specified time and at a specified temperature and conditions; normally 5 days at 20°C unless otherwise stated

Biological wastewater treatment Forms of wastewater treatment in which bacterial or biochemical action is managed to stabilize or oxidize the unstable organic matter present; oxidation ditches, aerated lagoons, aerobic lagoons, anaerobic lagoons, anaerobic digesters, and aerobic digesters are examples

Chemical oxygen demand (COD) Measure of the oxygen-consuming capacity of inorganic and organic matter present in water or wastewater, expressed as the amount of oxygen consumed by a chemical oxidant in a specified test; it does not differentiate between stable and unstable organic matter and thus does not necessarily correlate with biochemical oxygen demand

Digestion Usually refers to the breakdown of organic matter in a water solution or suspension into simpler or more biologically stable compounds, or both; in anaerobic digestion, organic matter may be decomposed to soluble organic acids or alcohols and subsequently converted to gases such as methane and carbon dioxide

Effluent Wastewater or other liquid treated or untreated that is discharged

Manure Fecal and urinary excretion of livestock and poultry, often referred to as livestock waste; this material may contain bedding, spilled feed, water, or soil, as well as wastes not associated with livestock excreta, such as milking center wastewater, contaminated milk, hair, feathers, or other debris

Solids content (1) Sum of the dissolved and suspended constituents in water or wastewater; (2) residue remaining after a sample of water, wastewater, or semisolid material is evaporated and the residue is dried at a specified temperature (usually 103°C for 24 hr); usually stated in milligrams per liter or percent solids

Waste management as related to agricultural sciences deals with the collection, transport, storage, treatment, and disposal or reuse of wastes associated with livestock and poultry production systems. It also encompasses the management, treatment, and disposal or reuse of wastewater, sludge, and solids generated from the processing of raw agricultural products, namely, fruits, vegetables, meat, poultry, fish, and dairy products. Selection of waste management systems is based on economics, engineering, public reactions, and regulations. Federal, state, and local regulations attempt to minimize or eliminate pollution through the development of waste management system by owners and operators.

TABLE I

Fresh Manure Production and Characteristics per 1000-kg Live Animal Mass per Day

			Typical live animal masses										
Parameter	Units		Dairy 640 kg	Beef 360 kg	Veal 91 kg	Swine 61 kg	Sheep 27 kg	Goat 64 kg	Horse 450 kg	Layer 1.8 kg	Broiler 0.9 kg	Turkey 6.8 kg	Duck 1.4 kg
Total manure	kg	mean	86	58	62	84	40	41	51	64	85	47	110
		std deviation	17	17	24	24	11	8.6	7.2	19	13	13	**[a]
Urine	kg	mean	26	18	**	39	15	**	10	**	**	**	**
		std deviation	4.3	4.2	**	4.8	3.6	**	0.74	**	**	**	**
Density	kg/m^3	mean	990	1000	1000	990	1000	1000	1000	970	1000	1000	**
		std deviation	63	75	**	24	64	**	93	39	**	**	**
Total solids	kg	mean	12	8.5	5.2	11	11	13	15	16	22	12	31
		std deviation	2.7	2.6	2.1	6.3	3.5	1.0	4.4	4.3	1.4	3.4	15
Volatile solids	kg	mean	10	7.2	2.3	8.5	9.2	**	10	12	17	9.1	19
		std deviation	0.79	0.57	**	0.66	0.31	**	3.7	0.84	1.2	1.3	**
Biochemical oxygen demand, 5 day	kg	mean	1.6	1.6	1.7	3.1	1.2	**	1.7	3.3	**	2.1	4.5
		std deviation	0.48	0.75	**	0.72	0.47	**	0.23	0.91	**	0.46	**
Chemical oxygen demand	kg	mean	11	7.8	5.3	8.4	11	**	**	11	16	9.3	27
		std deviation	2.4	2.7	**	3.7	2.5	**	**	2.7	1.8	1.2	**
pH		mean	7.0	7.0	8.1	7.5	**	**	7.2	6.9	**	**	**
		std deviation	0.45	0.34	**	0.57	**	**	**	0.56	**	**	**
Total Kjeldahl nitrogen	kg	mean	0.45	0.34	0.27	0.52	0.42	0.45	0.30	0.84	1.1	0.62	1.5
		std deviation	0.096	0.073	0.045	0.21	0.11	0.12	0.063	0.22	0.24	0.13	0.54
Ammonia nitrogen	kg	mean	0.079	0.086	0.12	0.29	**	**	**	0.21	**	0.080	**
		std deviation	0.083	0.052	0.016	0.10	**	**	**	0.18	**	0.018	**
Total phosphorus	kg	mean	0.094	0.092	0.066	0.18	0.087	0.11	0.071	0.30	0.30	0.23	0.54
		std deviation	0.024	0.027	0.011	0.10	0.030	0.016	0.026	0.081	0.053	0.093	0.21
Ortho phosphorus	kg	mean	0.061	0.030	**	0.12	0.032	**	0.019	0.092	**	**	0.25
		std deviation	0.0058	**	**	**	0.014	**	0.0071	0.016	**	**	**
Potassium	kg	mean	0.29	0.21	0.28	0.29	0.32	0.31	0.25	0.30	0.40	0.24	0.71
		std deviation	0.094	0.061	0.10	0.16	0.11	0.14	0.091	0.072	0.064	0.080	0.34

[a] **, No data available.

I. Waste Characteristics

A. Livestock Manure Characteristics

Livestock manure production and characteristics are important in the planning, design, and operation of livestock waste management systems. The descriptive data in Table I for livestock manure are drawn from a wide base of published information. When site-specific data or actual sample analyses can be performed, those data should be used for the planning, design, and operation of livestock waste management systems in lieu of the data in Table I. [*See* ANIMAL WASTE MANAGEMENT.]

B. Food Processing Wastewater Characteristics

Food processing can result in considerable quantities of solid waste and wastewater. Many of the wastes can be used in by-product recovery procedures. Solid waste from food processing may contain a high percentage of raw product and may exhibit characteristics of the raw product. Wastewater, on the other hand, is a dilute material that may contain low concentrations of some of the components of the raw product.

Dairy food processing waste characteristics are presented in Table II, and meat and vegetable wastewater characteristics are presented in Tables III and IV. The characteristics of solid fruit and vegetable wastes are presented in Table V. [*See* DAIRY PROCESSING AND PRODUCTS; MEAT PROCESSING.]

TABLE II
Dairy Food Processing Wastewater Characteristics

	Wastewater	
Product/operation	Mass (kg/kg milk processed)	BOD_5 (kg/1000 kg milk received)
Bulk milk handling	6.1	1.0
Milk processing	4.9	5.2
Butter	4.85	1.46
Cheese	2.06	1.8
Condensed milk	1.85	4.5
Milk powder	2.8	3.9
Milk, ice cream, and cottage cheese	2.52	6.37
Cottage cheese	6.0	34.0
Ice cream	2.8	5.76
Milk and cottage cheese	1.84	3.47
Mixed products	1.8	2.5

II. Livestock Waste Management

A livestock waste management system may consist of collection, storage, treatment, transfer, and utilization.

A. Collection

Collection refers to the initial capture and gathering of the waste from the point of origin or deposition to a collection point. Livestock and poultry manure collection often depends on the degree of freedom that is allowed the animal. If animals are allowed to move freely in a given space, the manure will be deposited randomly. Components of manure collection may include paved alleys, gutters, and slotted floors, as well as associated mechanical and hydraulic equipment to transfer the manure to storage.

Alleys are paved areas where the animals walk and may have a solid floor or a slotted floor. On slotted floors, animal hoofs work the manure through the slots into the alleys below. Paved alleys are used for beef, swine, and dairy and may be used below caged layers in poultry operations. The manure is collected by flushing or scraping the alleys. Mechanical scrapers are propeled by an electrical driver attached by cables or chains, and tractor scrapers are used in irregular-shaped alleys and open areas where mechanical scrapers cannot function properly. A tractor scraper can be a blade attached to either the front or rear end of a tractor or a skid-steer tractor that has a front-mounted bucket. Scrape alley widths generally vary from 2.5 to 4.3 m for dairy and beef and from 1.0 to 2.5 m for poultry and swine.

Alleys can also be cleaned by flushing. Slope is critical and generally varies from 1.25 to 5%. The length and width are also important factors in flush alleys, which should generally be less than 60 m long and vary in width from 1.0 to 3.0 m depending on the animal type. A number of mechanisms are used for flushing alleys, the most common being the emptying of large tanks of water or the use of high-volume pumps.

Gutters are narrow trenches used to collect animal wastes and are employed in confinement stall or stanchion dairy barns and in some swine facilities. Deep, narrow gutters with Y, U, V, or rectangular cross-sectional shapes that drain by gravity may be used in swine facilities. Narrow gutters can also be cleaned by flushing. Scrape gutters are frequently used in

TABLE III

Meat Processing Wastewater Characteristics

Component	Units	Red meat				
		Slaughter	Packing	Processing[a]	Poultry[a]	Broiler[b]
Volume	Liters/1000 kg[c]	406	610	737	1458	
Moisture	%					95.0
TS	% w.b.					4.9
	kg/1000 kg[c]	4.7	8.7	2.7	6.0	
VS	kg/1000 kg[c]					4.30
FS	kg/1000 kg[c]					0.65
BOD_5	kg/1000 kg[c]	5.8	12.1	5.7	8.5	
N	kg/1000 kg[c]					0.30
P	kg/1000 kg[c]					0.084
K	kg/1000 kg[c]					0.012

[a] Quantities per 1000-kg product.

[b] All values % w.b.

[c] Per 1000-kg live mass killed.

confined-stall dairy barns. The gutters are 41 to 61 cm wide and 30 to 41 cm deep with no bottom slope.

B. Storage

Storage is the temporary containment of the waste. The length of storage depends on the weather, crop, growing season, equipment availability, soil, soil conditions, labor requirements, and management flexibility. Manure can be stored as a solid, semisolid, slurry, or liquid.

Waste storage structures can be used for manure that will stack and can be handled by equipment designed for solid manure. The structures can be open or roofed to control excess moisture. Seepage and runoff must be controlled from open stacks. The structures often have wooden, reinforced concrete, or concrete block sidewalls. In some instances, manure may be stored in open stacks in fields. The amount of bedding material often dictates whether or not manure can be handled as a solid.

Waste storage ponds can be used to store solid and semisolid manure. They are earthen impoundments used to retain manure, bedding, and runoff liquid. The manure will likely be removed as a liquid unless precipitation is low or a means of draining the liquid is available. The ponds may have to be lined with compacted clay soil or artificial liners to prevent seepage and groundwater contamination.

Liquid and slurry manure can be stored in waste storage ponds or in aboveground or belowground tanks. Earthen storage is generally the least expensive type of storage. Storage ponds are generally rectangular but may be circular or any other shape that is practical. Manure storage tanks can be constructed of metal, concrete, or wood. Belowground tanks can be loaded using slotted floors, push-off ramps, gravity pipes, gutters, or pumps. Aboveground tanks are typically loaded by a pump moving the manure from a reception pit. Tank loading can be from the top or bottom of the tank. Waste storage ponds must provide not only volume to store wastewater and manure, but also storage capacity for normal precipita-

TABLE IV

Vegetable Processing Wastewater Characteristics

Component	Units	Cut bean	French style bean	Pea	Potato	Tomato
TS	kg/1000 kg[a]	15	43	39	53[b]	134
VS	kg/1000 kg[a]	9	29	20	50[b]	
FS	kg/1000 kg[a]	6	14	19	3[b]	
COD	kg/1000 kg[a]	14	35	37	71[c]	96
BOD_5	kg/1000 kg[a]	7	17	21	32	55

[a] kg/1000-kg raw product.

[b] Total suspended solids.

[c] Percentage of TSS.

TABLE V

Fruit and Vegetable Solid Waste Characteristics (Percent Wet Mass Basis)

Fruit/vegetable	Moisture content	Total solids	Volatile solids	Fixed solids	N	P	K
Banana, fresh	84.0	16.0	13.9	2.1	0.53		
Broccoli, leaf	86.5	13.5			0.30		
Cabbage, leaf	90.4	9.6	8.6	1.0	0.14	0.034	
Cabbage, core	89.7	10.3			0.38		
Carrot, top	84.0	16.0	13.6	2.4	0.42	0.03	
Carrot, root	87.4	12.6	11.3	1.3	0.25	0.04	
Cassava, root	67.6	32.4	31.1	1.3	1.68	0.039	
Corn, sweet, top	79.8	20.2	19.0	1.2	0.67		
Kale, top	88.4	11.6	9.7	1.9	0.22	0.06	
Lettuce, top	94.6	5.4	4.5	0.9	0.05	0.027	
Onion, top, mature	8.6	91.4	84.7	6.7	1.37	0.02	
Orange, flesh	87.2	12.8	12.2	0.6	0.26		
Orange, pulp	84.0	16.0	15.0	1.0	0.24		
Parsnip, root	76.3	23.7			0.47		
Potato, top, mature	12.8	87.2	71.5	15.7	1.22		
Potato, top, tuber					1.60	0.25	1.9
Pumpkin, flesh	91.3	8.7	7.9	0.8	0.12	0.037	
Rhubarb, leaf	88.6	11.4			0.20		
Rutabaga, top	90.0	10.0			0.35		
Rutabaga, root	89.5	10.5			0.20		
Spinach, stems	93.5	6.5			0.065		
Tomato, fresh	94.2	5.8	5.2	0.6	0.15	0.03	0.30
Tomato, solid waste	88.9	11.1	10.2	0.9	0.22	0.044	0.089
Turnip, top	92.2	7.8				0.20	
Turnip, root	91.1					0.34	

tion and runoff (less evaporation) during the storage period. Storage volume requirements for tanks are the same as those for ponds except that in most cases outside runoff is excluded from the waste storage tanks because of the relative high cost of storage.

C. Treatment

Treatment is any function that reduces the pollution potential of the waste, including physical, chemical, and biological treatment. It also includes activities that are classified as pretreatment, such as the separation of solids. Treatment methods used for agricultural wastes include the use of lagoons, oxidation ditches, and composting; these processes reduce nutrients, destroy pathogens, and reduce solids.

Anaerobic lagoons are widely used to treat animal wastes and are designed on the basis of the volatile solids loading rate. The rate of solids decomposition is a function of temperature, therefore the design loading rate varies from one location to another. Lagoons should be constructed to avoid leakage and potential groundwater pollution. If an anaerobic lagoon is managed and designed properly it will reduce animal waste odors. Anaerobic lagoons generally range in depth from 2 to 6 m.

Aerobic lagoons can be used if minimizing odors is critical. These lagoons operate within a depth range of 0.6 to 1.5 m to allow for the oxygen entrainment that is necessary for the aerobic bacteria. Aerobic lagoons are designed on the basis of the biochemical oxygen demand added per day and they should never be overloaded or they will become anaerobic. Surface area requirements are much larger for aerobic lagoons than for anaerobic lagoons.

Aerated lagoons operate aerobically and are dependent on mechanical aeration to supply the oxygen to treat the waste and minimize odors. This type of lagoon combines the small surface area feature of an anaerobic lagoon and the relative odor-free operation of an aerobic lagoon. The main disadvantages of aerated lagoons are the energy requirements and cost to operate the mechanical aerators and the high level of management required. Surface aerators that float on the surface of the lagoon or diffused-air systems may be used, the former being generally more economical to operate.

Oxidation ditches may be used for treating animal wastes in situations where there is not sufficient space available for a lagoon and odors are critical. The shallow, continuous ditch generally has an oval layout. It has a special aerator spanning the channel, and the action of the aerator moves the liquid waste around the channel and keeps the solids in suspension. Oxidation ditches can be expensive to operate and take considerable management.

Composting is the aerobic biological decomposition of organic matter, usually in solid and semi-solid form. Generally organic waste is mixed with other ingredients such as straw, wood chips, or corn cobs in a prescribed manner to accelerate the process. It converts an organic waste into a stable organic product by converting nitrogen from the unstable ammonia form to a more stable organic form. The end result is a product that is safer to use than raw organic material. Composting also reduces the bulk of organic material, improves its handling properties, reduces odor, fly, and other vector problems, and can destroy weed seeds and pathogens. The three basic methods of composting are windrow, static pile, and in-vessel.

The windrow method involves the arranging of compost mix in long, narrow piles or windrows. To maintain aerobic conditions, the compost mixture must be periodically turned. The minimum turning frequency varies from 2 to 10 days depending on the type of mix, volume, and ambient temperature. As the compost ages, the frequency of turning is reduced. Windrows are generally 1.2 to 1.8 m deep and 1.8 to 3.0 m wide.

The static pile method consists of mixing the compost material and then stacking the mix on perforated plastic pipe through which air is drawn or forced. The compost mixture height generally ranges from 2.4 to 4.6 m and the width is usually twice the depth.

The in-vessel composting process involves placing the compost in a container where it is continuously or periodically stirred. It is not as popular as the windrow or static pile methods, primarily due to cost and greater mechanical complexity.

Manure contains products that can be reclaimed by mechanical separation for feed or bedding. Solids in dairy manure can be removed and processed for use as a bedding material. Mechanical separators are also used to remove solids to reduce the volatile (organic) solids loading and in some cases the required volumes of storage facilities and of lagoons. Screens and centrifuges are commonly used to separate solids; screens are statically inclined or in continuous motion to aid in separation. Solids must be processed before they can be used for feed or bedding. If they are intended for bedding, the material should be composted or dried; if the solids are used for feed, they may need to be mixed with other feed ingredients and ensiled.

In many instances it is beneficial to remove manure, solids, and soil from the runoff from livestock operations. The most common device to accomplish this is the settling basin, which is a shallow pond designed for low velocities and the accumulation of solids. It is positioned between the wastewater source and storage or treatment facilities.

D. Transfer

Transfer refers to the movement and transportation of the waste throughout the system, including the transfer of waste from the collection point to the storage facility, to the treatment facility, and to the utilization site. The waste may require transfer as a solid, liquid, or slurry depending on the total solids concentration.

Liquid and slurry manure can be moved by gravity if sufficient elevation differences are present. For slurry manure a minimum of 1.2 m elevation is required between the top of the collection pit and the surface of the manure in storage. Gravity-flow slurry manure systems typically use 46- to 76-cm-diameter pipe.

Manure scraped from open lots can be loaded into manure spreaders or storage or treatment facilities using push-off ramps or docks. A ramp is a paved structure leading to a manure storage that can be level or inclined, whereas a dock is a level ramp that projects into the storage or treatment facilities.

Either displacement or centrifugal pumps are used to transport or agitate manure. Piston and air-pressure transfer displacement pumps are used for transferring manure, whereas diaphragm and progressive cavity displacement pumps are used for agitating, transferring, and irrigating manure, as are centrifugal pumps.

E. Utilization

Utilization is the function for which the manure and wastewater (effluent) is used for a beneficial purpose. The typical method is to apply animal manure to cropland, pasture, and hayland as a source of nutrients for plant growth and of organic matter to improve soil tilth. Manure and wastewater should be applied at rates at which the nutrient requirements of the crop are met. In many instances, nitrogen is the element that is used to determine the amount of manure to be applied. When nitrogen is used as the limiting nutrient, excessive phosphorus will be applied for most crops and manures. Today there is concern for the buildup of excessive phosphorus levels in soils where manure is applied. In some areas or watersheds, phosphorus is beginning to be used as the limiting nutrient for manure application.

Manure may also be utilized for energy. Liquid manure confined in an airtight vessel decomposes and produces methane, carbon dioxide, hydrogen sulfide, and water vapor as gaseous by-products in a process known as anaerobic digestion. Biogas, the product of anaerobic digestion, is typically composed of 55 to 65% methane, 35 to 45% carbon dioxide, and traces of ammonia and hydrogen sulfide. Biogas can be burned in boilers to produce hot water, in engines to power electrical generators, and in absorption coolers to produce refrigeration. The hydrogen sulfide present in biogas may cause the gas to have an odor similar to that of rotten eggs. Hydrogen sulfide mixed with water vapor can form sulfuric acid, which is highly corrosive. The most frequent problem with anaerobic digestion is related to the economical use of the biogas.

III. Food Processing Waste Management

The food processing industry has three possibilities for treating their wastewaters: (1) they may be treated separately in an industrial wastewater treatment plant; (2) raw wastewaters may be discharged to a municipal treatment plant for complete treatment; or (3) the wastewater may be pretreated at the site prior to discharge to a municipal wastewater treatment plant. Treated wastewater may be disposed of by stream discharge or applied to land. Federal and state regulations determine the minimum level of effluent quality that must be obtained for stream discharge and land application.

A. Pretreatment

Most food processing plants that discharge to municipal wastewater treatment plants use some form of pretreatment. Pretreatment processes may include both physical and chemical treatment processes, including screening, sedimentation, flotation, and flocculation.

Screening is one of the initial pretreatment steps in waste treatment and four types of screens are commonly used in the food processing industry. The most common screens are 840–420 microns, and fine screens (less than 74 microns) can also be used. The most common type of screen is the static screen, followed by the vibrating or oscillating screen; other types are the rotary drum screen, tangential screen, and rotating drum centrifugal screen. Selection of the type of screen to use will depend on initial cost, operating and maintenance costs, space required, hydraulic capacity, and percentage of solids captured.

The sedimentation process is used to remove settleable organic and inorganic solids suspended in the influent. Sedimentation tanks or clarifiers, as they are sometimes called, are rectangular or circular. Solids are removed by gravity or by skimming in the case of floatables. Wastewater moves through the sedimentation tank very slowly, giving the settleable solids an opportunity to sink to the bottom of the tank. Sedimentation tanks should be at least 3.0 m deep.

Dissolved-air flotation is a treatment process that removes suspended solids in the form of floating sludge. Air flotation involves the atmospheric pressurizing of the wastewater stream and the injection of air into the stream. Then as this mixture is released into an open tank, the air releases from the bulk fluid as small bubbles. The removal of suspended solids depends on the attachment of fine air bubbles to each suspended solid particle. These bubbles improve the buoyancy of the suspended particle, causing it to float to the surface where it is removed by mechanical means. Air flotation has an advantage over gravity sedimentation when used for the removal of oils, fine particulate matter, and fat, which are not readily amenable to sedimentation. Dissolved-air flotation is particularly useful in the treatment of poultry and meat packing or processing wastewater.

In some cases difficulties are encountered in the removal of suspended solids because of the size and density of the particles. To aid in the removal of these suspended solids, flocculating agents are used, which help to physically entrap the suspended particles through electrostatic interactions and adsorption. The entrapment results in the formation of larger and more dense particles that become amenable to sedimentation. Flocculating agents commonly used are lime, ferric chloride, ferrous sulfate, aluminum sulfate, and organic polymers. Organic polymers are generally used in conjunction with inorganic flocculating agents.

B. Biological Treatment

Biological treatment systems are "living" systems that rely on mixed biological cultures to break down waste organics and remove organic matter from solution. Biological treatment is the most important step in wastewater treatment. Generally sedimentation will only remove 35 to 50% of the BOD. Activated sludge, trickling filters, rotating biological contactors, and lagoons are common aerobic biological treatment processes used in the food processing industry. Some emerging technologies that have recently been used in the food processing industry include sequencing batch reactors and fluidized beds. Some anaerobic treatment processes are also used to treat food processing wastewater, and these may be used in combination with aerobic processes.

The activated sludge system is a process in which a mixture of wastewater and activated sludge is combined, agitated, and aerated. The activated sludge is a floc of biologically active material composed of viable microorganisms and suspended solids that have been developed from defined agitated and aeration conditions. The mixture of activated sludge solids and raw wastewater is referred to as the mixed liquor suspended solids. After a specific aeration time, the mixed liquor suspended solids enter a settling basin, where the solids are allowed to settle out and returned to the head of the aeration tank. Excess solids are removed from the settling basin as sludge and thickened and treated. Air or oxygen is supplied to the activated sludge process by mechanical means. There are a number of variations of the activated sludge process. Common processes used in the food processing industry are conventional activated sludge, contact stabilization extended aeration, and the oxidation ditch. Use of sequencing batch reactors in which aeration and settling are done in the same tank is a new modification of the activated sludge process.

In comparison to the activated sludge process, other forms of biological treatment use contact surfaces containing fixed biological material that extracts the pollutants from the wastewater stream. Common surface contact systems are trickling filters, rotating biological contactors, fluidized beds, and biofilter activated sludge processes.

In the trickling filter system, wastewater is distributed over a bed of media. Modern trickling filters use synthetic media whereas older trickling filters have crushed rock. Wastewater flows through the media to which the microorganisms are attached. As the biomass builds up on the media, at some point it will be sloughed off from the surface and fall to the bottom of the bed, where it is carried with the wastewater to a settling tank, where it is settled out and returned to the head of the system and settled out in a primary clarifier. Trickling filter depths may range anywhere from 1.5 to 6.1 m.

In the rotating biological contactor, the organic waste is extracted from the waste stream by biota film attached to rotating contact surface disks. The disks are usually 3.7 m in diameter and made of lightweight plastic. Approximately half of the disk is immersed in a trough containing the wastewater. The disk rotates slowly to allow proper film contact with the wastewater, and brings an adsorbed film of wastewater into the air where the film absorbs the available oxygen. The adsorbed biota film continues to grow and is ultimately sloughed off by the shear force of the rotating disc. The sloughed solids flow out with the treated wastewater to a final settling tank, where they are settled out. The rotating biological contactor discs will generally be placed in a series.

In a fluidized bed reactor, the wastewater to be treated passes upward through a bed of fine-granulated material, such as sand, at sufficient velocity to suspend the media. The reactor requires relatively little space to operate. The biofilter activated sludge process has a trickling filter followed by an aeration tank. Return activated sludge is recycled to the trickling filter.

One of the most common treatment processes in the food processing industry is the use of lagoons, which are relatively maintenance free and generally located in rural areas where land is available. The types of aerobic systems used are aerated lagoons, tertiary ponds, and facultative stabilization ponds. The latter depends on a symbiosis relationship within the aquatic ecosystem and on wind disturbances for physical incorporation of dissolved oxygen into the water. Generally the upper depths of the pond are aerobic whereas the bottom of the pond is anaerobic. The design depth varies from 1.0 to 2.0 m.

Tertiary ponds are less than 1 m in depth and have a low BOD loading. The principal use of a tertiary pond is to reduce the residual BOD and suspended solids in the wastewater that has been treated by another biological system such as activated sludge or trickling filter. The tertiary pond is also used to remove nitrogen and phosphorus from the wastewater. They are also referred to as polishing ponds.

The aerated lagoon incorporates the use of mechanical agitation and aeration to provide a complete-mixing aerated aquatic environment. These lagoons are commonly aerated with floating or platform-mounted mechanical aeration units. Aerated lagoons are generally 2.4 to 3.7 m deep.

The number and type of anaerobic treatment systems being used in the food processing industry have grown rapidly since the late 1970s and early 1980s. Prior to that, only anaerobic lagoons and a few anaerobic contact process systems were used.

Anaerobic lagoons are generally single celled and are the oldest and most frequently used anaerobic technology in the food processing industry. They generally range from 3.0 to 6.0 m deep and have anaerobic conditions throughout the lagoon because of the relatively high BOD loading rate. They are used primarily in the meat and poultry industries. A more recent development involves placing synthetic covers over anaerobic lagoons, for covered lagoons have higher BOD removal rates, and odors and biogas are captured.

The anaerobic contact process is analogous to the aerobic activated sludge process and relies on a completely mixed reactor to maximize biomass and food contact. The key components of the contact process are the completely mixed reactor, the biomass degassing unit, and the solids separation device. Settled solids are returned from the clarifier to the mixed reactor. The anaerobic contact process has been applied to meat processing wastewaters since the late 1950s.

Two new technologies that are being used are the upflow anaerobic sludge blanket (UASB) process and the anaerobic filter. The UASB process employs a single reactor containing a bed of active granular anaerobic sludge covered by a blanket of flocculent, less dense sludge. Influent wastewater is evenly distributed beneath the bed and flows upward through the two zones of biomass, each 1 to 2 m in depth. A three-phase separator is employed at the top of the reactor to separate biogas and solids from the liquid.

Anaerobic filters employ fixed media within a reactor to support the development of high concentrations of active biomass. Media can range from rock to pall rings to reticulated polystyrene. The systems can be operated in either the upflow or downflow mode.

C. Disinfection

The purpose of disinfection of any wastewater is to protect the public health from the spread of disease by controlling the point-source discharge. The practice of disinfection is carried out where wastewater treated for feces has been treated and discharged to a stream. Some state regulatory agencies require all point-source discharges to be disinfected. The methods use chlorine, ozone, and ultraviolet light, with chlorination being the most widely used disinfection practice.

D. Sludge Treatment and Disposal

Sludge from biological treatment processes and from the pretreatment processes of sedimentation and dissolved-air flotation must be stabilized. In some cases sludge is thickened before it is stabilized to increase the solids content. Sludge may be thickened by sedimentation or dissolved-air flotation.

Sludge is stabilized before ultimate disposal to stabilize and reduce the solids and reduce odors. The most common methods of stabilization are anaerobic digestion and aerobic digestion, the former consisting of two distinct stages that occur simultaneously in a digester. The first stage consists of hydrolysis of the high-molecular-weight organic compounds and conversion to organic acids by acid-forming bacteria; the second stage is gasification of the organic acids to methane and carbon dioxide by the methane-forming bacteria. Anaerobic digesters are closed structures with either floating or fixed roof covers. The digesters may be one or two stage.

Aerobic digesters are operated under aerobic conditions. Sludge is aerated in open basins for an aeration time of 10 to 20 days. Organic solids reduction can run as high as 40%.

Sludge can be further stabilized after digestion by composting. The objectives of composting are to biologically stabilize the organics, destroy pathogenic organisms, and reduce the volume of the sludge. The optimum moisture content for a compost mixture is 50 to 60%. Dewatered sludge is mixed with either an organic amendment like dried manure, straw, or sawdust or a recoverable bulking agent like wood chips. Composting may be performed in an enclosed vessel, where the compost mixture is slowly agitated, or in windrows or static piles with forced aeration. The windrows have to be turned periodically.

After sludge is aerobically or anaerobically digested it may be dewatered if it is not to be applied to land as a liquid. Digested sludge may be dewatered with open sand drying beds or by vacuum filtration, pressure filtration, or centrifugation. Pressure filtration dewatering is done using either a belt filter press or a plate-and-frame filter press. Vacuum filters require considerable energy so they are being replaced by belt filter presses, which are more economical to operate and produce a drier sludge cake. Modern sand drying beds have paved areas with watertight walls sloping to drainage trenches filled with a coarse sand bed supported on a gravel filter with a perforated pipe underdrain. Sludge is applied to a depth of 30 cm or more and may be pumped from the digester. Supernatant (sludge liquid) is drawn off after the solids settle and the solids are left to dry. The solids are removed from the drying fed by a front-end loader.

Sludges may be disposed of on land or in landfills, or may be incinerated. Sludges are applied to cropland, forestland, or disturbed lands undergoing land

TABLE VI
Comparison of Design Features of Alternative Land Treatment Systems

Feature	Slow rate (type 1)	Slow rate (type 2)	Rapid infiltration	Overland flow
Application techniques	Sprinkler or surface	Sprinkler or surface	Usually surface	Sprinkler or surface
Annual hydraulic-loading rate, meters/year	1.7–6.1	0.6–2.0	6.1–91.5	7.3–56.7
Minimum preapplication treatment provided	Primary sedimentation	Primary sedimentation	Primary sedimentation	Screening
Disposition of applied wastewater	Evapotranspiration and percolation	Evapotranspiration and percolation	Mainly percolation	Surface runoff and evaporation with some percolation
Need for vegetation	Required	Required	Optional	Required

reclamation. Composted sludges may be used as a potting soil medium or sold as a soil amendment.

E. Land Application

Land treatment methods can be classified into three main groups: slow rate, rapid infiltration, and overland flow. These alternatives differ considerably with respect to both treatment objectives and site characteristics. Comparison of design features for the different types of land treatment systems is presented in Table VI.

The slow rate system is the most widely used treatment process. Wastewater is applied to vegetated land by sprinkler irrigation or by surface irrigation methods such as graded border or furrow irrigation. The water applied is either consumed through evapotranspiration or percolates vertically or horizontally through the soil profile where treatment occurs. There are typically two types of slow rate systems. The system listed as type 1 in Table VI generally has a higher hydraulic loading rate. Its design objective is wastewater treatment and the limiting design parameter is usually soil permeability or constituent loading. The type 2 system has the design objective of water reuse through crop production or landscape irrigation.

Rapid infiltration systems have relatively high application rates compared to those of slow rate systems. Wastewater is applied on an intermittent schedule usually to shallow infiltration or spreading basins. In some cases high-rate sprinklers are used. Vegetation is not used in infiltration basins but is required with high-rate sprinklers. In a rapid infiltration system the wastewater that is applied may be allowed to recharge groundwater and help augment water supplies or prevent saltwater intrusion or may be recovered using underdrains or pumped withdrawal. The treatment potential of rapid infiltration systems is somewhat less than that of slow rate systems.

Overland flow systems utilize the vegetative cover as a treatment component and consist of a series of graded slopes and terraces. Slopes are generally 2 to 5% and the length of the slopes may be from 46 to 76 m. Wastewater is applied at the top of the slope or approximately one-third of the distance down the slope by high-pressure sprinklers, low-pressure sprays, or surface methods such as gated pipe. The amount of the waste water lost will depend on the time of year and local climate. In many systems, over 60% of the applied water is collected as runoff on an annual basis.

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Water: Control and Use

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Glossary

Aquifer Water-bearing formation beneath the land surface that provides a good water reservoir; a formation, group of formations, or part of a formation that contains sufficient permeable material to be capable of yielding significant quantities of water to wells and springs

Ground water That part of the subsurface water that is in the saturated zone or, more generally, all water which occurs below the land surface as distinct from surface water

Hectare Metric unit of area equal to 10,000 square meters (approximately 2.5 acres)

Hydrologic cycle Continuous process whereby water which falls as precipitation from the atmosphere evaporates from land and water surfaces and, after condensation in the atmosphere, is deposited again on earth as precipitation

Permeable Condition of a geologic material that renders it capable of transmitting a significant quantity of water without impairment of the structure of the geologic material

Surface subsidence Lowering of the land surface above a ground water aquifer resulting from a consolidation of the aquifer material produced by dewatering all or part of the aquifer by pumping or other drainage procedures

Surface water All fresh water which occurs on the earth's surface, including overland flow, stream and river flows, lakes, and surface ponds and reservoirs

Tonne Metric unit of weight equal to 1000 kilograms (approximately 2200 pounds)

Water demand Quantity of water required during a particular time interval for a particular use or purpose

Water is essential to life, growth, and reproduction. On a global scale, water is the energy regulator of the heat budget of the earth. Without the evaporation of water, life on earth would be impossible. As an energy carrier, it makes possible water power, steam power, and space heating. It is a pervasive solvent for such diverse processes as industrial production and for the use of soil nutrients by plants. Water is essential for plant photosynthesis and for all animal life, including human. Finally, water provides a means of transport—for navigation, for drainage canals, for recreation, and for waste water. Accordingly, provision of an adequate supply of water is a major goal throughout the world.

I. Introduction

This article deals with the problem of matching the water demands of society to available water supplies. For the globe as a whole, there are adequate supplies of water. However, the temporal and spatial distributions of these supplies frequently do not match with the demands of society. In many places water shortages limit agricultural production, industrial output, and the capacity to support increasing populations. To the extent possible demands for water are met by the development of control systems which consist of physical facilities to collect, store, and redistribute water in accordance with the spatial and temporal requirements of society. [*See* WATER RESOURCES.]

Redistribution of water requires that changes be brought about in the naturally occurring physical system. These changes often deplete both the quantity and quality of the water in parts of the natural hydrologic system and thus produce negative impacts. It is important that these potential negative impacts be carefully evaluated, and to the extent possible, mitigated, for all water resource development projects.

A. The Global Supply of Water

Of the vast quantities of water on the earth—about 1.4 billion cubic kilometers—97.4% is in the oceans. The remaining 2.6%—about 36 million cubic kilometers—is fresh water, and of this, 77% is found in polar icecaps, icebergs, and glaciers. Nearly 90% of the remaining fresh water is found in ground water. The rest of the fresh water is found in rivers, lakes, animals and plants, and the atmosphere. It is clear that the usable water on the land surfaces of the earth (often termed the renewal water supply), on which most terrestrial life and our entire economy are dependent, constitutes only a minute fraction of the total water of the earth. However, this tiny fraction of the world's water is vital to life on the planet, and humans depend on it for such uses as water supply, food, transportation, and recreation.

B. The Distribution of the Global Supply

As stated above, for the globe as a whole, there is no shortage of water. However, the distribution of the global supply in both the spatial and temporal dimensions is often not consistent with needs as evidenced by the fact that there are severe shortages of water, as well as severe floods, in many parts of the world. Strong natural and manmade factors combine to reduce the water available to specific regions and localities in the right amount, at the right time, and of the required quality.

The most important natural force involved in the distribution of water on the Earth's surface is the dynamic character of the biosphere. Part of the water supply is in a continuous process of change from the solid (snow and ice) and liquid forms to the vapor state and then back again as precipitation. This part of the supply evaporates from water and land surfaces and, after condensation in the atmosphere, is deposited again on earth. Through the precipitation process, evaporation and runoff water from land and water surfaces are replaced as fresh water. This circulation pattern is termed the *hydrologic cycle*. It is, in effect, a gigantic still.

C. Surface and Ground Water Supplies

Water for use by humans is drawn from two sources—surface water and ground water. Surface water is found in streams, rivers, reservoirs, and lakes. Ground water is drawn from aquifers or underground reservoirs. For the globe as a whole, and in most localities, surface water is at present the most important source. In the United States, for example, about 80% of the water used (exclusive of hydropower generation) is withdrawn from surface water. However, ground water is a major source in many parts of the world. The great Ogallala aquifer in the United States is the largest known aquifer in the world, and it supplies water to large parts of the Midwest, particularly to Colorado, Kansas, Nebraska, New Mexico, Oklahoma, and Texas. Other large aquifers are found in India, China, Iraq, Syria, Russia, and Egypt. [*See* GROUND WATER.]

Much of the water in aquifers is millions of years old, and less than 1% of the water content of aquifers is replenished each year. When ground water withdrawals exceed replenishments, the aquifer is said to be "mined." In many parts of the world today, ground water that has accumulated over millions of years is being rapidly mined to meet demands resulting from population growth and expanded energy and agricultural uses.

When ground water levels recede because of overdraft, increased energy and capital equipment are needed to meet demands. Eventually the costs of lifting water can exceed the benefits, and the existing uses, such as for irrigation, have to be abandoned. This situation has already come about in many regions of Texas and Arizona. Clearly, there can be environmental and energy benefits to pumping aquifers at the same rate as the annual recharge instead of mining ground water. It should be emphasized that sustained ground water mining can cause aquifer consolidation and thus a permanent loss of aquifer storage capacity and surface subsidence.

II. Water Control

A. Water Distribution Systems

As previously stated, human activity is an important element affecting the global distribution of water. Some human actions affect the distribution of water adversely. For example, floods are a scourge that continue to plague many parts of the world, particularly poor countries that lack the resources and infrastructure to cope with them. Often floods downstream are caused by human activity upstream. A well-known example is the upstream deforestation in Nepal and India that causes downstream flooding in Bangladesh.

Other human activities degrade the quality of water. The pollution of important rivers and streams in the United States by municipal and industrial wastes during the first half of this century is an obvious case in point.

However, many human activities affect the supply of water constructively. An immense set of manmade physical facilities exists to increase the local supply of water, to control potentially destructive forces, and to enhance the quality of water. An example is the Central Utah Project, which collects water from the streams on the south slopes of the Uintah mountain range, stores it in reservoirs, and transports it through the Wasatch mountain range to be used for irrigation, for municipal and industrial purposes, and to generate electrical energy. Another important example is the huge multipurpose project involving the waters of the Nile River in Egypt. These physical facilities are the components of local and regional supply systems—reservoirs, wells, pumps, pipelines, aqueducts, and canals. The human resources include farmers, technicians, engineers, and managers. The institutional resources include corporations, financial institutions, a framework of customs, laws, agreements, operating rules, governmental agencies, nongovernmental organizations, and educational institutions. These facilities and institutions convert the raw water in streams and aquifers into a developed resource—water that can be supplied for either withdrawal or for instream uses on a reliable basis.

B. Agricultural Distribution Systems

Once water has been controlled by a dam, diversion, or ground water well, it can be conveyed and distributed to croplands for use. If this distribution is well planned, designed, operated, and maintained, it will deliver water at a rate, frequency, and duration that optimize crop production. If it is not, it will limit crop production, exacerbate waterlogging problems, and degrade the quality of nearby streams, lakes, reservoirs, and/or ground water basins. [*See* IRRIGATION ENGINEERING: FARM PRACTICES, METHODS, AND SYSTEMS.]

The distribution system begins at the *headworks*, which are structures or combinations of structures located near the controlled source of water which withdraw water into the distribution system. Headworks consist of intake structures, screens and debris-removal devices, and water-measurement structures. From the headworks water flows through the *conveyance network* toward *turnouts* where it is delivered to irrigators. The *conveyance network* is composed of canals or pipelines. Control and management of water in the conveyance network requires a large number of structures to regulate water levels and flow, dissipate energy, and monitor flow rates. Conveyance networks generally branch into successively smaller canals and/or pipes to direct the water over an area where crops are being grown. It is common to name the various canal or pipeline branches in order to describe the component of the distribution system to which one is referring. For example, the terms "main canal," "branch canal," "distributary canal," and "minor canal" are used to represent first-, second-, third-, and fourth-order canal segments. The main canal supplies water to the branch canal which in turn supplies the distributary, and so on.

The structural elements of the distribution system are visible and important because they determine the cost of the system and how it will impact the environment around it. However, the most important aspect of distribution systems is how they are operated, because this determines how well these systems meet their goals of providing irrigation water at a rate, frequency, and duration that will optimize crop production. The operation of a distribution system is defined by restrictions on the water supply (such as water rights), the nature of the agency actually responsible for operating the system (government or private organization), and how irrigators use water at the farm level (growing rice as opposed to growing wheat, for example). Most often the operation of the distribution system can be classified as *demand*, *rotation*, or *continuous flow*. A demand-based operation is controlled by the needs of the croplands which are communicated to the distribution system operators by the irrigators. Rotation systems are more structured and allocate time among the irrigators according to relatively fixed rules for sharing the water. Continuous flow occurs when the water supply is not regulated but is delivered to the irrigators continually. The choice of operating scheme has tremendous impact on the use of water at the farm level. Demand systems are flexible and productive but are harder to achieve and thus require a greater level of skill and training. Rotation and continuous flow schemes are simpler to operate but at the same time provide a less useful water supply at the farm where it is used.

III. Uses of Water

A. Offstream Uses

Offstream uses include domestic and commercial consumption, manufacturing, agriculture, energy production (primarily cooling and water for steam-powered generation of electricity), and the minerals industry. Total global consumptive demand for off-stream uses is expected to continue to rise. Rural consumptive demand for domestic uses is expected to remain fairly constant at less than 2% of the total whereas urban consumptive requirements for domestic purposes are expected to rise slightly but remain at approximately 13% of the total. Industrial requirements, at 15% of the total, approximately equal domestic uses.

A full 70% of all offstream water is used for irrigation. This water is vitally important to the maintenance and expansion of agricultural production. The major focus of this article is on the functions of irrigation and on the problems facing the use of water for agricultural production.

B. Instream Uses

This form of water use is often referred to as *instream-flow* needs; that is, the amount of water flowing through a natural stream channel needed to sustain instream values at acceptable levels. Values of instream flow relate to uses made of water in the stream channel, including fish and wildlife population maintenance, outdoor recreation activities, navigation, hydroelectric generation, pollution control, conveyance to downstream points of diversion, and ecosystem maintenance (including freshwater requirements of estuaries, riparian vegetation, and flood-plain wetlands). Streamflow sufficient to meet all of these requirements establishes the acceptable level for instream-flow uses. Understandably, at a given location in a particular stream system, only certain uses may be applicable.

C. Growth of the Demand for Water

During the 20th century the demand for water has increased rapidly for two reasons. First, population growth alone has generated additional needs for water. Second, per capita demand has risen with global economic growth and urbanization. As a consequence, "global water use doubled between 1940 and 1980, and is expected to double again by the year 2000. Two thirds of the projected use will go into agriculture. Yet 20 countries with 40 percent of the world's population already suffer water shortage." (Postel, 1984).

This increase in consumption, leading in many countries to competition for the scarce resource, is a major factor generating needs for effective water management. The shortages lead to competition and confrontation not only internally but between countries as well.

D. Focus on the Agricultural Uses of Water

1. Food Production Using Irrigated Agriculture

Water is the major limiting factor for agricultural production worldwide. Crops require and transpire massive amounts of water. For example, a corn crop that produces 6500 kg of grain per hectare will take up and transpire about 4.2 million liters of water during the growing season. Irrigated crop production requires large quantities of water. For instance, the production of 1 kg of the following food and fiber products under irrigation requires on the average: 1400 liters for corn, 1900 liters for sugar, 4700 liters for rice, and 17,000 liters for cotton. The amount of water required to produce 1 kg of grain-fed meat ranges from 4200 to 8300 liters when the water requirement for irrigated grain is included.

The use of water by crops is the prime reason that agriculture returns a relatively small portion of the water applied in irrigation. Approximately 60% of the water applied in irrigation is consumed and does not return to streams for reuse. In contrast, only about 5% of the water pumped for public supplies is consumed.

Irrigation has been used to increase agricultural production since the dawn of agriculture. However, until about the beginning of the 19th century, irrigation systems were small, and most eventually failed because they did not provide for salinity control. The estimated area of irrigated land in the world in 1880 was about 8 million hectares (Gulhate, 1958). This figure reached about 40 million hectares by 1900. As experience was gained in planning, constructing, and operating irrigation projects, the global irrigated area expanded rapidly. By 1985, of the approximately 1.5 billion hectares of cultivated land in the world, about 271 million hectares, or 18%, were irrigated (*Worldwatch Institute*, 1987, p. 125).

Irrigation produces special pollution problems when stream water is degraded by the addition of salts in returning drainage waters. For example, when irrigation water is withdrawn from the Colorado River in the Grand Valley at Grand Junction, Colorado, and later returned to the river, an estimated 18 tonnes per hectare of salts are leached from the irrigated land and added to the river water. At times during the summer, the Red River in Texas and Oklahoma is more saline than seawater, mainly due to irrigation use and normal evaporation.

Whereas the overall contribution of irrigation to agricultural production is clear, the precise contribution varies widely around the world. Irrigation may be applied to the desert, where rainfall rarely occurs, such as in Egypt or southern Iraq. It may replace or supplement rainfall agriculture, as in dry-farming regions of the United States; it may make possible multiple-cropping in areas where only single-cropping is otherwise possible because of wet and dry seasons, as in Bengal or Senegal; or it may serve as insurance against damaging, short-term droughts, as in the eastern United States. The uses of irrigation include sporadic spreading of meager spring flood waters in the deserts of the Middle East, sprouting a thin crop of wheat, and carefully controlled, optimal applications under the sophisticated technology used in the southwestern United States. [*See* DRYLAND FARMING.]

2. Irrigation Systems

When water is diverted through a turnout from the distribution system it enters the control of the on-farm component of agriculture, or the *irrigation system*. There are three basic types of irrigation systems: (1) surface irrigation systems, (2) sprinkle irrigation systems, and (3) drip irrigation systems. Each of these has many configurations. Surface irrigation, for example, is often described by the terms "furrow irrigation," "border irrigation," or "basin irrigation." Sprinkle irrigation has individual members like "center-pivots," "side-roll" or "wheel-line," "big gun," and others. Drip irrigation is also known as "trickle irrigation" and has special configurations as do surface and sprinkle irrigation systems.

Surface irrigation systems distribute water over a field using gravity. Flow is introduced to the field at one point, then moves over the land surface, wetting the soil as it progresses. Surface irrigation has been practiced for thousands of years and today comprises more than 90% of irrigation worldwide. Some countries, such as the United States, have about 55% surface irrigation and some, such as Israel, have very little, but these are exceptions rather than rules. Surface irrigation is relatively inexpensive to implement, but unless care is given to proper design and management, application efficiencies will be as low as 40 to 50%. Modern land-leveling equipment and computerized design methodologies have helped to implement surface irrigation systems with efficiencies as high as 90%. The major advantages of surface irrigation include low cost, low energy requirements, and, where water is plentiful, low irrigator skill. The major disadvantages include potentially low efficiencies and the land leveling requirement.

Sprinkle irrigation systems distribute water using an orifice to convert pipeline pressure into the kinetic energy of a jet issuing from the orifice. As the jet emerges from the orifice, it breaks into individual droplets. Under ideal conditions, the droplets would be distributed uniformly over an area around the orifice. In practice, however, it is impossible to construct an orifice which achieves perfect uniformity, and the droplet patterns of several sprinklers are overlapped to approximate uniform coverage. Sprinkle irrigation systems are recommended and used on practically all types of soil, topography, and crops. It is a flexible and efficient system of irrigation. The main disadvantages of sprinkle systems are that they have a high initial cost, they typically use substantially more energy than surface irrigation, they are accompanied by higher evaporation losses, and they require more maintenance than surface irrigation systems. Land leveling is not required and application efficiencies of 60% are common. Unlike surface and drip systems, sprinkle systems may be used for other reasons, such as temperature control, evaporative waste disposal, and seed germination.

Drip irrigation systems also use an orifice to convert pipeline pressure into the kinetic energy of orifice discharge, but do so differently. In a drip irrigation system the orifice is designed to dissipate nearly all of the kinetic energy in the flow so that when it emerges from the orifice it moves slowly. Drip systems, therefore, irrigate a small area around each orifice, which is generally called an emitter. Drip systems usually irrigate widely spaced or row crops where an individual pipeline can be located nearby to provide one or more emitters to each plant. The slow flows and the individual plant locations give drip irrigation very precise water control which translates into application efficiencies of 90% or greater. Since only a small surface area is wetted, evaporation losses are negligible. Drip systems apply irrigation water to crops much more often than either surface or sprinkle systems. This high-frequency irrigation regime has been shown to increase crop yields. The disadvantages of drip systems include high cost, the necessity of water supply filtration and treatment, and in some cases, the buildup of salts in the soils. Drip irrigation does not represent a large percentage of irrigation worldwide, but it is an important technology for special applications.

IV. Water Management

In many parts of the world, the food supply depends upon extensive irrigation development. For example, on the Indian subcontinent, which has one-fifth of the population of the world, water supply seriously limits agricultural production on 65% of the arable land and prevents year-round production on an additional 29%. The Green Revolution, while providing a potential for important food supply increases, cannot reach that potential without substantial and sustained improvement in the management of available water and soil resources, especially in arid and subhumid areas. These regions comprise approximately one-sixth of the total land surface and a substantially greater portion of the world's potential for agricultural production. Virtually all irrigated or potentially irrigable portions of the globe face serious management problems involving water, soil, and crop production systems.

A. Water Management Needs

A number of powerful factors act to force conscious management of water resources throughout the world. These factors operate in all societies, political systems, and stages of development. The political and administrative adaptations designed to deal with them vary widely, but the fundamental forces do not differ.

Often there is not enough water to meet unlimited competing demands, and means of mediating among the various potential uses must be devised. The kinds of uses typically continue to increase, and means of meeting these new needs must be found. The management needs include flood mitigation, land drainage, sewer systems, culvert design, water supply, irrigation, hydroelectric power generation, and navigation. Demands on a single water source may include withdrawals for use on irrigated land, in factories, or in towns and cities; falling water for hydropower; impoundments for recreational lakes or for flood control; flow of streams for carrying wastes or for navigation; and maintenance of wetlands for waterfowl. If upstream users discharge large quantities of wastes into a river, the supply of usable water available to downstream users is diminished. In some withdrawal uses (such as hydropower generation), most of the water is returned to the stream in good condition. In others, notably irrigation, much of the water is lost through consumptive use, and the returning drainage waters usually carry increased salt levels.

Each of these uses has its peculiar requirements in terms of quantity, quality, location, and timing, and these often conflict. Water resource development projects—canals, wells, dams, impoundments, pumps, and so forth—generally require large capital investments, and it takes time to construct them. Years elapse between authorization, planning, and construction to operation. Additionally, the installations are durable and thus "freeze" the pattern of water management of a region for generations, influencing rates of economic growth, levels of health, and amenities of living. Taking an intelligent long view is an important aspect of successful water management.

Until fairly recently the major concern was to develop the physical, economic, and institutional control procedures necessary to make water available for a specific purpose. Now, however, water systems generally involve multiple-purpose projects. In addition, it is necessary to manage water resources in the context of the total environment. Thus, water resource planning and management need to be integrated with comprehensive planning and management plans for entire river basins or regions.

Water management is further complicated by the fact that the problem is seldom one of simply how much water but rather of how much water of a particular quality is acceptable or needed for a given use at a given time. Pollution is a prime example of the problem of quality. Pollution reduces the utility of water for municipal and irrigation purposes and threatens aesthetic values.

B. Administrative Structures for Management

Because of the powerful competing interests involved, administrative structures have been developed to control the distribution of water. The formalities and complexities of these structures vary widely, depending upon need and cultural background. For some projects, typically the smaller ones, the administrative mechanisms can be quite informal and simple. However, for large and extensive projects, such as those which exist in California, complex administrative structures for managing water resources are necessary.

In the more complex systems, there are water-source controllers, producers of water, transmitters of water, users of water, and reclaimers of water. The first three levels are usually, but not always, institutions. Users frequently are individual farmers. Reclaimers may be individuals, but because there are aspects of reclamation that can be controlled only by community action, this function generally is most satisfactorily implemented by an institution with adequate control authority.

The authority to make decisions in such complex systems is virtually always decentralized. Each management level usually has its own authority for decision making, subject to physical, legal, and indirect social constraints of the public at large and of other interacting levels. Such a structure is a hierarchical multilevel decision-making system with multiple goals and objectives that are often not commensurable. Each level is optimized at the stage at which it occurs in the system, subject to constraints imposed by both higher and lower decision-making levels. Ideally, all levels are then subjected to an overall analysis for optimality of the trade-offs among various compatible and noncompatible objectives at all levels. Efficient and effective water resource management can be achieved only by considering all facets—engineering, social, political, and economic. Sometimes this situation exists, but often it does not.

C. Special Management Needs for Irrigated Agriculture

The basic elements of irrigation water management systems consist of (1) water supplies, including storage and distribution works; (2) crop production subsystems as they are affected by irrigation, leaching, and drainage; (3) underlying ground water storage areas that interact with the crop production system; and (4) social and institutional subsystems within which production is accomplished, resources are made available, and various levels of policy are established and implemented. These processes are strongly interrelated. They constituite a dynamic and continuous system, with each component of the system influencing, and, in turn, being influenced by, other components. Applying irrigation water to a field, for example, might satisfy the soil moisture requirements of the crop, but failure to recognize the need for drainage might lead to establishment of an undesirably high water table and/or salinity conditions within the soil profile.

As is true of all water management, effective irrigation water management systems must be designed and operated to fit within a broad social–political–biological environment. For instance, in the early days of irrigation in the western United States, physical facilities were built to transport water to the land, but the failure to recognize the need for effective social–political–economical institutions at the user level resulted in the bankruptcy and collapse of many of these early developments.

V. Conclusions

Water is controlled and regulated to serve a wide variety of purposes including flood mitigation, irrigation, supplies for culinary and industrial purposes, transportation, the generation of electrical energy, wildlife preservation and culture, aesthetics, and recreation. Flood detention reservoirs, storm drains, and dikes are examples of the types of structures used to control water so that it will not cause excessive damage to property, public inconvenience, or loss of life. Irrigation projects, hydroelectric power dams, municipal water supply works, and navigation improvements are examples of the use of water for beneficial purposes.

Because of its important role in global food production and because it uses a large proportion of our available fresh water supplies, irrigation is given special consideration in this article. Irrigation is the application of water to soil to supplement deficient rainfall to provide adequate water for plant growth. It has been practiced for centuries. Some of the works built in the Nile River Valley around 3000 B.C. still play an important part in Egyptian agricultural production. However, as the need for food continues to escalate and other conflicting uses enter the picture more strongly, there is an ever-increasing need for the efficient control and use of irrigation water.

As human demands on available land and water resources have increased, there has been a corresponding increase in the need to more carefully control and regulate the use of these resources. Physical facilities must be planned and implemented in the context of multiple, dynamic, and often conflicting social needs and demands. Included in these processes are the complex and increasing environmental issues and concerns. Thus, both well-designed physical facilities and effective management institutions and policies are essential to the efficient control and use of the earth's limited supply of available fresh water.

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Water Resources

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Glossary

Application satellites Satellite-based sensor systems being used in water resources are primarily two basic types. (1) *Earth resources satellites* include the Landsat (USA), SPOT (French), Meteor-priroda (USSR), ERS-1 (European), and J-ERS-1 (Japan). The Landsat remote-sensing system was first launched in 1972 and has been applied widely around the world for studying water resources. The type of sensor, band designation, spatial sensitivity range, and spatial resolution used in the Landsat system are listed in Table I. As Table I shows, the existing Landsat system has two important sensors, i.e., thematic mapper (TM) and multispectral scanner (MSS). Recently, the SPOT system has also been used. The SPOT has high-resolution visible (HRV) imagery which includes three bands (0.5–0.6, 0.6–0.7, and 0.78–0.9 μm) with 20-m resolution color mode, and 10-m resolution panchromatic mode (0.51–0.73 μm). (2) *Weather satellites* include NOAA-TIROS (USA), GOES (U.S.), Meteor-2 (USSR), Meteosat (European), GMS (Japan), and Feng-Yun (China). Most weather satellites include both visible and thermal infrared sensors.

Geographic information system (GIS) Computer system designed specifically to manage large volumes of geocoded spatial data derived from a variety of sources. The capabilities of a GIS system are to accept input data; to serve as a clearinghouse for data; to store, retrieve, manipulate, analyze, overlay, and display these data based on the requirements of the user; and to create both tabular and cartographic output which reflect these requirements.

Ground-penetrating radar Radar system, which currently operates in the frequency range of 80 MHz to 1 GHz, has been designed specifically to penetrate earthen materials. It radiates repetitive, short-duration, electromagnetic pulses into the soil from a broad-band-width antenna. Towing the antenna along the ground produces a continuous profile of subsurface conditions on the graphic recorder.

Land use/land cover Land use/land cover information has always been and continues to be an important element in the integration, planning, and management of water resources, agricultural resources, land resources, environment protection, economy, and landscape. A land-use classification system used by the United States Geological Survey (USGS) emphasizes remote sensing as the primary data source. This classification system as shown in Table II represents only the more generalized first and second classification levels. The approach to land use/land cover classification is "resource oriented," providing greater flexibility when separating data into distinguishable classes.

Remote sensing Gathering of information about an object without using an instrument in physical contact with the object. Humans' ears, eyes, and nose are typical natural sensors with limited capabilities. Today, based on scientific research and development, the remote-sensing techniques are being developed into ground-based, airplane-based, and satellite-based sensor systems.

Satellite image processing Satellite-sensed images

TABLE I

Comparisons of Type of Sensor, Band Designation, Spectral Sensitivity Range, and Spatial Resolution Used in Landsat Remote Sensing Systems

		Spectral sensitivity range		
Type of sensor (1)	Band (NASA designation) (2)	Wavelength (μm) (3)	Color (4)	Spatial resolution (m) (5)
		(a) Landsat 1 and 2[a]		
RBV[b]	Band 1	0.475–0.575	Blue-green	76
	Band 2	0.580–0.680	Yellow-red	76
	Band 3	0.690–0.830	Red-infrared	76
MSS[c]	Band 4	0.5–0.6	Green	76
	Band 5	0.6–0.7	Red	76
	Band 6	0.7–0.8	Near infrared	76
	Band 7	0.8–1.1	Near infrared	76
		(b) Landsat 3[a]		
RBV[b]	Two cameras	0.505–0.750	(Panchromatic)	40
MSS[c]	Band 4	0.5–0.6	Green	76
	Band 5	0.6–0.7	Red	76
	Band 6	0.7–0.8	Near infrared	76
	Band 7	0.8–1.1	Near infrared	76
	Band 8	10.4–12.6	Thermal infrared	234
		(c) Landsat 4 and 5[a]		
TM[d]	Band 1	0.45–0.52	Blue	30
	Band 2	0.53–0.61	Green	30
	Band 3	0.62–0.69	Red	30
	Band 4	0.78–0.91	Near infrared	30
	Band 5	1.57–1.78	Intermediate infrared	30
	Band 6	10.42–11.66	Thermal infrared	120
	Band 7	2.08–2.35	Mid infrared	30
MSS[c]	Band 1	0.5–0.6	Green	76
	Band 2	0.6–0.7	Red	76
	Band 3	0.7–0.8	Near infrared	76
	Band 4	0.8–1.1	Near infrared	76

[a] Launch dates: Landsat 1: 7/23/72, operation ended 1/6/78. Landsat 2: 1/22/75, operation ended 2/25/82. Landsat 3: 3/5/78, operation ended 3/31/83. Landsat 4: 7/16/82. Landsat 5: 3/1/84.

[b] Return beam vidicon camera.

[c] Multispectral scanner.

[d] Thematic mapper.

provide data to the computer which are digitally compatible with computer software developed for interpreting physical meaning on the earth surface. A public domain computerized image processing program used in the United States is the Earth Resources Laboratory Application Software (ELAS). ELAS is a software package designed and maintained by the National Aeronautical and Space Administration (NASA) to provide analysis and processing capabilities that enable the construction and manipulation of various geographical data files.

Water resources rank among the most important renewable natural resources on the earth in all of their three phases (i.e., liquid, solid, or vapor), and are one of the most fundamental requirements for agricultural production. The water resources most available for use in agriculture are derived from precipitation (i.e., rainfall and snowfall), rivers, lakes, reservoirs, and groundwater. Water resources research for agriculture concentrates on the collection of sufficient basic hydrologic cycle-related data for better planning and management of these re-

TABLE II

Land Use/Land Cover Classification System for Use with Remote Sensor Data by the United States Geological Survey

Level I	Level II	
1. Urban or built-up land	11	Residential
	12	Commercial and services
	13	Industrial
	14	Transportation, communications, and utilities
	15	Industrial and commercial complexes
	16	Mixed urban or built-up land
	17	Other urban or built-up land
2. Agricultural land	21	Cropland and pasture
	22	Orchards, groves, vineyards, nurseries, and ornamental horticultural areas
	23	Confined feeding operations
	24	Other agricultural land
3. Rangeland	31	Herbaceous rangeland
	32	Shrub and brush rangeland
	33	Mixed rangeland
4. Forest land	41	Deciduous forest land
	42	Evergreen forest land
	43	Mixed forest land
5. Water	51	Streams and canals
	52	Lakes
	53	Reservoirs
	54	Bays and estuaries
6. Wetland	61	Forested wetland
	62	Nonforested wetland
7. Barren land	71	Dry salt flats
	72	Beaches
	73	Sandy areas other than beaches
	74	Bare exposed rock
	75	Strip mines, quarries, and gravel pits
	76	Transitional areas
	77	Mixed barren land
8. Tundra	81	Shrub and brush tundra
	82	Herbaceous tundra
	83	Bare ground tundra
	84	Wet tundra
	85	Mixed tundra
9. Perennial snow or ice	91	Perennial snowfields
	92	Glaciers

sources for agricultural production on a sustainable basis.

I. Hydrologic Cycle

The endless recirculation of water in the atmosphere–hydrosphere–lithosphere is known as the hydrologic cycle. The cycle is the principal mechanism governing the distribution of water over the earth, balancing flows between the sea, the continent, and the atmosphere. The principal factor driving this endless recirculation is solar activity which controls the thermal regime of the earth and the atmosphere circulation. The hydrologic cycle can be studied according to the particular scale of reference, i.e., global scale, basin scale, etc. From the agricultural point of view, the basin-scale hydrologic cycle is emphasized. The basin-scale cycle is considered to be a continuous circulation of water from water vapor to precipitation, stream flow, lakes, reservoirs, soil moisture, groundwater, and out of basin transfer, to the return to water vapor through evaporation and transpiration. Within a basin, the dynamics of the hydrologic processes are governed mainly by the temporal and spatial characteristics of inputs and outputs, the land use/land cover conditions, the slopes, the soils, the underlying geology, and the implementations of irrigation and drainage.

II. Land-Use Classification

A. Conventional Techniques

In general, the conventional land-use classification methods have relied on ground observation and aerial photography, resulting United States Department of Agriculture–Soil Conservation Service (USDA-SCS) soil surveys, USGS topographic maps, USGS land use/land cover maps, and other such resources. The USGS standard topographic quadrangle maps cover 7.5 min of latitude and longitude and are published at the scale of 1 : 24,000. These maps show man-made features, water features, road classifications, urban areas, U.S. land lines, and woodland. The smallest mapping unit of the USGS land use/land cover maps for urban, water, mines, quarries, gravel pits, and certain agricultural land is four hectares in contrast to 16 hectares for the other categories. [*See* LAND USE PLANNING IN AGRICULTURE; SOIL AND LAND USE SURVEYS.]

B. Satellite Methods

The land use/land cover classification based on satellite images can be accomplished by two general methodologies. One method is a supervised classification technique in which the operator classifies an area of pixels (picture elements, i.e., sensor spatial resolutions) that belong to one or more specific categories of land use/land cover. The computer then uses one of many classifying algorithms to group pixels of similar spectral response. The other classification method is an unsupervised classification technique. In this method, the satellite images are loaded into the computer as mentioned in the supervised classification technique. The operator then determines how many different classes are desirable and the computer classifies each pixel into one of the statistically created classes. The computer uses a sophisticated set of algorithms to determine which pixel belongs to which class. The different classes are then related to individual land use/land cover complex represented by a color which can be viewed on the computer monitor. The location and spatial pattern are noted and compared with quadrangle maps and through extensive ground-truthing. Finally, the established classes are grouped into similar land uses to form the desired classes which can be stored in a GIS database.

III. Precipitation

A. Rainfall Estimation

1. Conventional Methods

The primary conventional method used in rainfall estimation is the raingauge measurement. The large spatial and temporal variability of rainfall distribution requires a dense raingauge network if acceptable accuracy of rainfall estimation is to be achieved. However, there is a nonlinear relationship between the increase in number of gauges and the improvement in accuracy, and the improvement is mainly for reducing the temporal variation. A dense network is also costly to maintain and operate. Furthermore, measurement of rainfall by gauges is affected in particular by the interrelated factors of topography, site, wind, and gauge design. The gauge catch may be representative of a small or large area depending upon rainfall event, slope, aspect, elevation, and location in relation to hills and ridges. Because of these inherent limitations of the raingauge design for rainfall measurements, point data could contain ambiguities producing an increase in uncertainty of regional estimates. [*See* METEOROLOGY.]

2. Remote-Sensing Methods

a. Cloud-Indexing Approach Using satellite-based visible and thermal-infrared data to characterize the cloud type or temperature for correlation with rainfall via empirical relationships is the basic concept of the cloud-indexing approach. This approach is time-independent, identifies different types of rain clouds, and estimates the rainfall from the number and duration of clouds.

b. Thresholding Approach This approach is based on satellite derived temperature thresholding and cloud brightness to identify potential rain clouds. This approach considers all clouds with low upper surface temperatures to be rain clouds.

c. Life-History Approach This approach is based on the premises that significant rainfall comes mostly from convective clouds, and that convective clouds can be distinguished from other clouds in satellite images. This approach is time-dependent and considers the rates of change in individual convective clouds or in clusters of convective clouds.

d. Pattern-Classification Approach This approach uses a statistical pattern-classification technique to assign rainfall to one of several classes according to such parameters as coldest cloud-top temperature, average cloud-top temperature, and average cloud-top temperature difference between two consecutive images.

e. Integration Approach This approach correlates a small-coverage (e.g., raingauge), high-resolution sensor with a large-coverage (e.g., satellite), low-resolution sensor, and then uses the large-coverage sensor to estimate the regional rainfall in a given area which is not covered by the small-coverage sensor.

f. Microwave Radiometry Microwave techniques offer a great potential for measuring rainfall because at some microwave frequencies clouds are essentially transparent, and the measured microwave radiation is directly related to the presence of rain drops themselves. Microwave radiometry or passive microwave techniques react to rain in two fundamental ways: by emission/absorption and by scattering.

g. Radar Raindrop and snow crystals can cause a backscatter of radio waves that could be detected through radar. Thus, attempts have been made to transform radar echoes into quantitative rainfall measurements using a reflectivity method. One important step involved in this method is to properly choose the parameters used in the radar reflectivity factor (Z)–rainfall rate (R) relation which is usually called a Z–R relation equation. This relation involves two calibration parameters called a and b which vary with rainfall types, seasonal vegetation condition, and the site of interest.

h. Lightning Flashes Rainfall has been thought to play a major role in separating the electric charge in thunderstorms, and in initiating lightning discharge. A state-of-the-art lightning detective network, the National Lightning Detection Network (NLDN), has operated with full coverage of the contiguous United States since 1989. The NLDN provides lightning flash occurrence time, location, polarity, stroke count, and regional amplitude in near real-time. These lightning flashes are being used to predict storm movement and rainfall rate.

B. Effective Rainfall

Effective rainfall is defined as a rainfall which is temporarily stored on the soil surface or in the soil without causing runoff or seepage to the groundwater. Effective rainfall is an important factor used to estimate the agricultural watershed runoff, the supplemental irrigation requirement, and the quantity of drainage. Since the water-table depth is inversely related to the soil moisture content along the soil profile above the water table, a deeper water table indicates a lower moisture content in the soil. That in turn, can increase the effective rainfall. A study of effective rainfall shows that about 3.4 cm of rainfall is stored in an organic soil for each 100 cm increment of water-table depth.

C. Snow Measurement

1. Conventional Methods

A popular technique of snow measurement is to measure 24-hr snowfall with a ruler, and to estimate the precipitation amount based on the assumption of the 10% of snow volume, i.e., using 10 cm of snow as equivalent to 1 cm of water. The snow gauge is also often used. Either ruler or snow-gauge measurements are made at several points to estimate snow cover.

2. Remote-Sensing Methods

a. γ Radiation Method This method takes advantage of the natural emission of low level γ radiation from the soil. An aircraft passes over the same flight line before and after snow cover and measures the attenuation resulting from the snow layer which is empirically related to an average snow water equivalent for the site.

b. Visible/Near Infrared Method Snow can readily be identified and mapped with the visible bands of satellite imagery because of its high reflectance in comparison to non-snow-covered areas. Generally this means selecting data from the National Oceanic and Atmospheric Administration (NOAA) weather satellite Advanced Very High Resolution Radiometer (AVHRR) visible band, Landsat MSS bands 4 or 5, SPOT, or Landsat TM bands 2 and 4. The contrast between clouds and snow is greater in the near infrared (i.e., Landsat TM Band 5) and this serves as a useful discriminator between clouds and snow.

c. Thermal Infrared Method Thermal data can be useful for helping identify snow/nonsnow boundaries and discriminating between clouds and snow with the NOAA weather satellite AVHRR data.

d. Radar The technique of using radar to measure snowfall is similar to the one used in rainfall measurement except that the calibration parameters are chosen differently.

IV. Soil Moisture Monitoring

A. Conventional Approaches

Soil moisture content information is an important parameter for studying soil water movement, evapotranspiration, irrigation scheduling, crop water stress, crop management, and hydrologic modeling. Conventional methods of measuring soil moisture content include tensiometer, neutron probes, gravimetric soil sampling, soil lysimetry, chemical method, and soil electrical resistance. These methods provide data for a point rather than large-scale areal measurements and are time consuming. An alternative technique for measuring soil moisture content for large-scale areas needs to be developed. [*See* SOIL-WATER RELATIONSHIPS.]

B. Remote-Sensing Approaches

1. Visible/Near Infrared Method

In general, wet surfaces have less reflectance values in both visible and near infrared than do dry surfaces.

However, the reflected solar radiation is dependent not only upon the soil moisture condition but also on confounding factors such as organic matter, structure, roughness, texture, mineral content, illumination geometry, angle of incidence, color, and plant cover. In other words, it is possible to develop a unique relationship between spectral reflectance and soil moisture for a specific site where the confounding factors are known or can be balanced out.

2. Mid-Infrared Method

Mid-infrared (MIR) reflectance is inversely related to the surface soil moisture content. Thus, the MIR data of the Landsat TM band 7 can be used to assess regional soil moisture conditions. This high-resolution assessment (i.e., 30 m) of regional soil moisture information would result in more efficient direction of ground-based investigators to areas with the most extreme (wet or dry) conditions.

3. Thermal Infrared Method

The thermal infrared (TIR) method is based on the observation that soil surface temperature is primarily dependent upon the thermal inertia of the soil. The thermal inertia, in turn, is dependent upon both the thermal conductivity and volumetric heat capacity. The inertia is an indication of soil resistance to the diurnal surface temperature fluctuation. A soil with a high thermal inertia (due to a high soil moisture content) will have a lower diurnal range of surface temperature. Temperature-based soil moisture estimation has been based on the use of temperature information collected in the form of TIR data using ground-based devices, airborne instruments, or satellites. The applicability of the ground-based and airborne TIR instruments has been limited to relatively small (field) scales of operation using either diurnal (maximum–minimum) temperature difference or surface–air temperature difference techniques. Although the weather satellites can provide half-hourly (GOES satellite) or several times daily (TIROS satellite) coverage of a large area, their applicability to soil moisture estimation is limited by the low spatial resolution (1–8 km) of their TIR imagery. However, the current Landsat satellites (4 and 5) have a TIR data band in the TM sensor (i.e., band 6) system which has a high (120 m) resolution. This single daily surface temperature data set from the Landsat TIR imagery can provide useful information for periodic (8 to 16 days) monitoring of the spatial distribution of soil moisture conditions mainly because the daytime temperature is inversely related to the soil moisture content. Therefore, Landsat TM TIR data have significant potential for the detection of the soil moisture condition of various land-use categories. The results might be implemented in such ways as land-use evaluation, land-use planning, preplanting soil moisture mapping, drought area assessment, and drainage zone identification.

4. Microwave Sensing Method

Both passive (radiometric) and active (radar) microwave systems can be used to measure soil moisture. The theoretical basis of this microwave sensing method consists of the dielectric properties of a soil, which are highly correlated with the soil moisture content.

V. Evapotranspiration Estimation

A. Conventional Approaches

Evapotranspiration (ET) is an important process in both hydrologic cycle and agricultural watershed management. Numerous techniques can be used to estimate ET using conventional approaches, such as mass (water vapor) transfer, energy budget, water budget, groundwater fluctuations, evaporation pan, empirical formulae, and combination (of energy budget and mass transfer) methods. Most of these are based on the relationship between free-water evaporation (or the transpiration of a freely transpiring crop surface) and the climatological parameters, mainly net radiation flux, temperature, wind speed, and relative humidity of the air. A variety of techniques have been developed partly in response to the availability or lack of certain data for ET estimation. Factors such as data availability, the intended use, and the time scale required by the problem must be considered when choosing the ET calculation technique. The combination method is known as the Penman method, which is superior to most empirical methods for ET estimation. However, the Penman method requires a variety of climatological data, such as maximum and minimum air temperatures, relative humidity, solar radiation, and wind speed. If some of these data are not available, alternative methods must be used for ET estimation. In choosing an alternative technique, one should minimize the input climatological data as much as possible without affecting the accuracy of estimation, so that the multicollinearity problem among the data can be eliminated and the data availability can be improved. [*See* IRRIGATION ENGINEERING, EVAPOTRANSPIRATION.]

B. Data-Short Environment

ET estimates are not available for certain parts of the world, because some basic climatological data and water budget data are not available for use in conventional methods. One alternative is to adopt the available ET estimates directly from other areas where crop and climatic conditions are similar. An approach used to diagnose the similarity between two areas is the Koppen climate classification which is based on the vegetation zones, temperature, rainfall, and seasonal characteristics. This alternative ET estimation method is good for an area lacking reliable climatic data. Another alternative is to generate synthetic climatic data to be used in conventional approaches of ET estimation. This alternative method is useful for an area that has some climatic data available that can be used as a basis for data generation.

C. Water-Use Efficiency Index

A water-use efficiency index (WUEI) is defined as the additional crop yield per unit ET. The WUEI can be grouped into high, medium, and low categories. High WUEI values indicate that less water is used for producing per unit of additional crop yield. For dry-biomass production, the WUEI varies from greater than 35 kg ha^{-1}/mm for the high category, to between 15 and 35 kg ha^{-1}/mm for the medium category, and to less than 15 kg ha^{-1}/mm for low category. For grain production, the WUEI is about 5 kg ha^{-1}/mm less than that for dry-biomass production in each category. The C_4 plants (i.e., plants whose first carbon compound in photosynthesis consists of a four-carbon atom chain) are mostly classified into the high WUEI category and C_3 plants (i.e., plants whose first carbon compound in photosynthesis is composed of a three-carbon atom chain) into the medium and low WUEI categories. If a regional crop yield is known, the WUEI information can be used to estimate regional ET. This WUEI information can be used as a potential tool to develop criteria of water allocation for crop production.

D. Remote-Sensing Approach

Remote-sensing techniques cannot measure evaporation or ET directly. However, remotely sensed data support methods for extending empirical relationships based on either vegetation mapping or climatic factors (such as temperature and solar radiation) which are used in ET estimation. The Landsat MSS data have been used to map the littoral zone vegetation of lakes to adjust the effective surface area to account for ET and improve the total water budget computation of lakes. Water surface temperature has been measured using the TIROS satellite data to estimate the lake surface evaporation. Estimates of the net radiation from GOES satellite data can be used to estimate ET. The resulting moisture flux is then used to develop a water balance model for predicting crop yields.

VI. Groundwater

A. Water Table Investigation

Water table information, as a part of the shallow groundwater aquifer, is important to monitor roots reaching the capillary fringe of the water table, changes in vegetation types and pattern, potential ET, effective rainfall, soil moisture, irrigation, drainage, and runoff. The established approach for measuring water table depth has been the observation of water levels in monitor wells. This method is reliable and provides detailed information about the water table at a specific location. However, most investigations require groundwater information over the entire region of interest, with data indicating both depth and distribution of the water table. Unless sufficient monitor wells are installed, necessary information on regional water table depth is incomplete and interpretations must be inferred from a limited number of widely spaced observation wells. Errors often arise as a result of the incompleteness of sampling. Alternative approaches using state-of-the-art geophysical techniques are available. Many of these techniques provide continuous spatial measurements that can improve water table interpretations significantly and help alleviate some of the problems inherent in point-sampling methods. Though still in the developmental phase, the ground-penetrating radar (GPR) is designed specifically as a readily available tool for shallow, subsurface site investigations. In earthen materials, the GPR has provided continuous data of subsurface conditions from depths of less than 1 m to more than 30 m. Landsat MSS data bands 4, 5, and 7 have also been used in conjunction with aerial photographs to assess perched water tables. Furthermore, aerial photograph interpretation and satellite data analysis can provide the location of aquifers from surface features which should precede ground surveys and fieldwork. Temperature difference techniques as mentioned in the soil moisture section can also be used to infer or identify shallow groundwater and springs or seeps. Synthetic aperture radar (SAR) and side-looking radar (SLAR) data have a great potential for groundwater exploration, especially in arid and hyperarid regions. [*See* GROUND WATER.]

B. Flowing Well Assessment

The artesian wells flowing uncontrolled in many parts of the world have caused a serious saline-contamination problem. Locating these wells by ground search is made difficult by the urbanized or reforested condition of former agricultural land. Both ground-based color infrared (GCIR) and aerial color infrared (ACIR) photographs taken for analysis of the spectral reflectance of land-surface features can provide information for detection of flowing wells. Both GCIR and ACIR showed similar patterns of spectral reflectance for the same component class of land-surface features. Well-site soil has a higher spectral reflectance than similar soil not associated with a well. Well water has a higher spectral reflectance than natural pond. Most vegetation types have differences in spectral reflectance magnitude. The scatter diagram of green and red channels of spectral reflectance video-digitized from ACIR photography appears to be useful for classifying land-cover types and distinguishing flowing well sites. Both Landsat and SPOT satellite data have been used to identify former agricultural land and providing clues for well assessment.

VII. Agricultural Water Quality

A. Water Quality Determination

Remote sensing has an important role in water quality evaluation and management strategy. Sources of pollution are often easy to identify, especially when there are pipes or open channels discharging into a lake or river. Nonpoint source pollution can perhaps be evaluated best by remote sensing. Monitoring large areas on a frequent basis can only be achieved economically with remote-sensing techniques. In the meantime, remote sensing is limited primarily to surface measurements of turbidity, suspended sediment, chlorophyll, eutrophication, and temperature. However, these characteristics of water quality can be used as indicators of more specific pollution problems. Because the intensity and wavelength of reflected light are modified by the volume of water and its contaminants, an empirical relationship can be established between the reflectance measurements and certain water quality variables.

B. Wetland Assessment

Wetlands are of interest to water resource management as a natural vegetation filter for improving water quality in fresh water marshes. The studies have emphasized the form of nutrient uptake by wetland plants, detention time of water in the wetland, and best-management practices. Landsat data have been used to make estimates of wetlands water volumes on a monthly basis by combining depth/stage relationships with surface water area. The scatter diagram of band 4 and band 5 from Landsat MSS data can be used most efficiently to identify the wetland. An additional aspect of wetlands management involves the extent of dredging, lagoons, drainage, and other man-induced changes that have an impact on the natural environment. Remote sensing is well suited to monitor these changes and to make preliminary estimates of the environmental impact. The temporal aspect of Landsat and SPOT data allows changes to be observed over time and, in some cases, predevelopment baseline data to be obtained from earlier satellite scenes. [*See* WETLANDS AND RIPARIAN AREAS: ECONOMICS AND POLICY.]

VIII. Irrigation

A. Irrigation in Water Resources

In general, irrigation can be defined as the quantity of water released from an external source to adequately wet the crop root zone. Water source availability varies with space and time, and different crop root zones also have spatial and temporal characteristics which are extremely difficult to measure by conventional methods, such as ground-survey, but this information is very important to water resources planning and management. The alternative of using remote sensing in groundwater assessment, mentioned above, can be also used to assess surface water source, crop identification, and crop spatial coverage. [*See* IRRIGATION ENGINEERING: FARM PRACTICES, METHODS, AND SYSTEMS.]

B. Surface Water Source Assessment

1. Water Surface

Since land/water contrast is very strong in the near infrared band, Landsat and SPOT data can be used to delineate the water surface area from the surrounding land. As an example, the density slicing from Landsat MSS band 7 (i.e., near infrared) and the scatter diagram of bands 5 and 7 can be used to assess the water-surface area.

2. Water Volume

A technique is being developed to use a number of Landsat data sets covering the lakes of interest to correspond with a wide range of known lake stages. An average water surface area between two stages can be derived from the Landsat data. The change in lake volume is estimated from the change in stages multiplied by the corresponding average water surface.

3. Water Depth

Two methods have been used to remotely estimate the water depth of a lake. The first method is based on the measured water depth at control points as the dependent variable and satellite data as independent variables used to develop a regression model for water-depth estimation for areas other than the control points. The second method is based on a concept of the major vegetation associations in the littoral zone of a lake which are linked to elevation through the hydroperiod. The littoral zone vegetation map which can be derived from the satellite data is used to estimate ground elevation. The water depth is then estimated based on the deviation between the recorded lake water stage and the satellite-derived ground elevation.

C. Crop Identification

Most vegetation types have their own pattern of spectral response in the range from 0.36 to 1.11 μm. However, a general pattern of spectral response for live vegetation has a minimum response of approximately 0.68 μm, and three peaks occurring around the regions of 0.54–0.56, 0.75–0.90, and 0.95–1.05 μm. These peak regions could be applied to design satellite-based crop identification systems. As an example, the first peak of spectral response falls within the Landsat MSS band 4 and TM band 2; the second and third peaks fall within MSS band 7 and TM band 4. Therefore, the scatter diagrams of band 4 versus band 7 in MSS and band 2 versus band 4 in TM could be used for crop identification. Furthermore, the effect of a citrus canopy on SPOT image spectral response has been studied. Researchers found that the red and green bands are highly correlated with the citrus canopy. Therefore, it will be advantageous to include data from these two bands in any agricultural land-use classification scheme in areas where citrus crops are significant.

D. Crop Spatial Coverage

An irrigated crop has a higher spectral response in the near infrared region than the nonirrigated crop. The integration of historical satellite data with a GIS can provide not only the spatial distribution of irrigated crop coverage changes but also the expansion of agriculture into previously uncultivated areas.

IX. Drainage

A. Drainage in Water Resources

Agricultural drainage refers to the removal of excess field water which interferes with land forming, land preparation, tillage, crop growth, fertilizer application, weed control, insect and disease problems, field cultivation, and harvest operations. In general, this drained water typically has a water quality problem caused by improper insecticide, herbicide, and fertilizer applications. This field drainage water can influence regional water resources planning and management. Two major problem areas involved in agricultural drainage are identification of areas with drainage problems and the design of adequate systems for the drainage of excess field water. In some localities drainage problems are difficult to identify using the conventional ground-survey method. The alternative of using remote-sensing technique should be considered. Drainage-basin parameters such as physiographic features, topographic maps, vegetation state, drainage density, and drainage pattern are important information to have not only for designing a new drainage system but also for evaluating the existing drainage system. Using conventional ground-survey methods to obtain these basin parameters is expensive and difficult. The possibility of utilizing remotely sensed data should be encouraged. Furthermore, inadequate drainage is associated with and contributes to the severity of saline accumulation conditions which interfere with the growth of most crops.

Again, assessment of saline-affected areas is difficult to accomplish by conventional ground-survey methods. Therefore, the possibility of using remote-sensing technique should be investigated. [*See* SOIL DRAINAGE.]

B. Drainage Problem Identification

1. Perched Water Table

The Landsat and SPOT data in conjunction with aerial photographs can provide a potential methodology for identifying perched water tables.

2. Soil Color

The saline-affected area offer depicts a snowy halo of salt on top of the soil due to the evaporation of surface or near-surface water from perched water-table accumulation. The organic matter accumulated under a poorly drained condition also can cause a darker soil color than that under a well drained condition. These contrasts of soil colors can be identified using satellite visible images.

3. Plant Response

For tree crops growing in poorly drained soil, the first symptom is light green or yellow leaves which are sparser and smaller than normal. Defoliation follows, leaving a bare, dead framework of branches. These plant-response symptoms can be detected by visible and infrared images from the Landsat and SPOT satellites.

4. Drainage-Water Collection

The satellite data can be used to evaluate the seasonal variation of drainage water accumulation which can provide a clue for identifying some drainage problems. As an example, in Saudi Arabia, there is an old concept that the collected drainage water remains in lakes to evaporate during the whole year. However, the Landsat data showed that the drainage water flows to the sea in the winter season and diminishes during the summer season.

C. Drainage-Basin Parameters

1. Physiographic Features

The usual physiographic features such as basin shape, circularity, and stream orders can be discerned by satellite images.

2. Topographic Maps

Recent use of SPOT imagery and its stereographic capabilities have demonstrated its potential in topographic mapping.

3. Vegetation State

Vegetation state is an important parameter to be considered in drainage studies. The satellite visible red band is good for separating vegetation types and for delineating nonvegetated areas.

4. Drainage Density

The drainage density is defined as a ratio between the length of each channel segment in a basin and the drainage area of the basin. Both segment length and drainage area of the basin can be estimated through the use of Landsat and SPOT data.

5. Drainage Pattern

The drainage pattern which includes drainage network, stream length, and the location of ponds and lakes is readily obtained from satellite imagery. The visible red band is best for showing channel networks. The SLAR can penetrate the dense vegetation and produce an image that depicts drainage patterns.

D. Salinity Assessment

Satellite data have been used to detect saline soils with high water tables. It has been found that satellite data can be used to determine whether a soil is undergoing a salinization or a desalinization process. Recently, the GPR has been used to delineate the saline-affected area.

X. Agricultural Runoff Prediction

A. Conventional Method

The impact of land use changes on the basinwide runoff is of interest to many water resources planners and managers. There is a conventional technique called the USDA-SCS curve number method which is widely used to estimate the peak discharge for a drainage basin. This method utilizes an important parameter called runoff curve number (CN). The CN is an index of runoff potential and is a function of soil type, the land-use condition, and the antecedent soil moisture. Thus, recently this method has been used as an index to assess the land-use change effect on basinwide runoff for three reasons. First, the soil type within a basin does not effectively change with time. Second, the antecedent soil moisture affected by weather conditions is assumed to be stable for long-term average conditions. Third, the basinwide runoff is a summation of subbasin runoffs and the maximum potential difference between rainfall and runoff is linearly related to the CN. Therefore, the basinwide runoff index could be estimated from a weighted CN which can be obtained from either the overall land-use classification or from the subbasins. Thus, the prime variable in the basinwide runoff index estimation is land-use change with time. In addition, a hydrologic soil grouping established by the SCS labels soils as A, B, C, and D. These groups are determined by infiltration rate and soil permeability. Group A soils are well drained, coarse sandy soils having the lowest runoff potential. Group D soils consist of heavy clays, are the most poorly drained, and have the highest runoff potential. Groups B and C are ranked approximately between these extremes. These soil hydrologic groups in combination with the land use/land cover information are used to select the appropriate CN from a chart. In the past CNs have been calculated using a wealth of ground-survey land use/land cover information. However, as mentioned above in the land-use classification, the land-use change data gathered by the conventional method are expensive and difficult. An alternative to be investigated is the use of satellite imagery to assess land-use changes.

B. Remote-Sensing Method

The role of remote sensing in runoff predictions is generally to provide a source of input data or as an aid to estimating equation coefficients and model parameters. There are three general areas where remote-sensing data are currently being used as input data for a runoff investigation. First, these remotely sensed data are very useful for obtaining information on watershed geometry, drainage network, and other map-type information. Second, remote sensors produce input data for an investigation of empirical flood peaks, annual runoff, or low flow equations. These two applications use satellite imagery in the same way that aerial photography has been used. Third, runoff models (e.g., SCS curve number method) that are based on a land-use component have been modified to use land-use classes from satellite image classification.

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Weed Science

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Glossary

Allelopathy Production of phytotoxins or chemical growth retardants by a plant which stunts the growth of or kills competing plants

Biocontrol Use of other organisms (e.g., microbes, insects, or nematodes) to manage weeds

Competition Reduction of a plant's supply of some necessary factor for growth and survival by another plant

Herbicide mode of action Physiological and biochemical mechanism through which a herbicide inhibits growth or kills a plant

Herbicide-resistant crop Crop made resistant to a herbicide through biotechnological methods

Interference Negative interactions between two plant species (generally a crop and a weed); interference consists of both competition and/or allelopathy

Mycoherbicide Fungal plant pathogen used to manage weeds

Safener Compound used to protect a crop from herbicides

Weed Plant in a place and at a time when it is unwanted by humankind

Weed science is the scientific study of all aspects of weeds and their management. It is an eclectic discipline that incorporates expertise from many other sciences, including botany, chemistry, biochemistry, agronomy, plant physiology, plant pathology, plant genetics, soil science, ecology, and economics. A large proportion of weed science research has dealt with the science of herbicides; their synthesis, their use, their physiological and biochemical modes of actions, and their behavior in the environment.

I. Background and Economics

Weeds are ubiquitous and continually changing pests in agricultural and other settings. Before the 20th century, when most of humankind were subsistence farmers, people dealt with weeds primarily through brute force. They used labor-intensive, mechanical methods such as hoeing, hand pulling, and cultivation with animal-drawn implements. Cultural methods, such as rotating crops or selecting a competitive crop variety, were also useful in reducing weed pressures. The origin of weed science as a separate scientific discipline can be traced to the need for less labor-intensive methods of weed management with the movement from agrarian to metropolitan societies in developed countries.

Before World War II, there were agronomists and other scientists who specialized in weeds and their management; however, weed science did not exist as a separate discipline. The discovery of modern herbicides during World War II and the advent of their commercial availability after the war spurred the organization of weed control specialists to formalize weed science as specific scientific discipline. Just as plant pathologists and entomologists are driven primarily by the need to control and manage plant pathogens and insects that are agricultural pests, the ultimate objective of most weed science research is to reduce the costs, environmental damage, and toxicological effects of weeds through improved management strategies and methods.

Weeds cause multibillion dollar economic losses every year; perhaps $20 to $30 billion in the United States alone. To determine the entire cost of weeds, the costs of control measures and the economic damage of uncontrolled weeds must be computed. Furthermore, weeds poison people, pets, and livestock, reduce the esthetic value of property, provide alternate hosts for undesirable insects and plant pathogens, block waterways and irrigation channels, and adversely affect water quality in aquaculture and recreational pursuits. No part of our food or natural fiber supply is immune from the negative effects of weeds. The need for cost-effective and environmentally safe weed management is great, and the need increases in developed and developing countries as the farm labor supply shrinks.

II. Weed Biology and Ecology

A. Biological and Physiological Attributes of Weeds

At first glance, weeds and crops appear to be quite similar. They are both usually fast-growing, determinate higher plants. Weed scientists have attempted to discover the biological and physiological traits which might distinguish particularly troublesome weeds from crops and other plants. Several generalizations can be made. First, weeds often grow better than crops under stressful environments such as drought, flooding, low light, or temperature extremes. Thus, most weeds are at a competitive advantage over crops under such conditions. Second, unlike most other noncrop plant species, the life cycle, biology, and physiology of weeds is usually well-adapted to areas of disturbance, such as tilled fields, lawns, and ditches. Third, most of the major weeds in agricultural ecosystems are reproductively prolific by either seed production and/or asexual means (tubers, rhizomes, stolons, etc.). There are many exceptions to various aspects of these generalizations because of the diverse and changing ecological niches that can be filled by weeds in agricultural and other settings. For example, parasitic weeds such as dodder (*Cuscuta* spp.) and witchweed (*Striga* spp.) are most successful under environmental conditions that normally favor the crop. However, they are similar to other weeds in that they are reproductively prolific.

Unlike crops, weeds are not introduced into the environment by planting at the beginning of favorable growing conditions. Therefore, in most climates, weeds must persist in the environment during unfavorable conditions (e.g., winter or dry seasons). Annual weeds overcome unfavorable climate with dormant seeds, and perennial weeds use a variety of strategies, including dormant seeds, buds, rhizomes, tubers, etc. Whether annual or perennial, these hardy propagules must have precise regulation of dormancy so that loss of dormancy does not occur at unfavorable times or places. For example, seedlings from very small weed seeds will not survive if the seed germinates at a soil depth too great for the seedling to emerge. Therefore, weed propagules are particularly well equipped to sense both quantity and quality of light, temperature, atmospheric gases, and other environmental signals for breaking dormancy at the proper time, in the appropriate microenvironment.

In cultivated crops, the weed seed bank is an important determinant of weed populations. When weeds are not effectively controlled, high numbers of weed seed are produced and cultivated into the soil. In many weed species, the seed can remain dormant for many years. Every year, cultivation brings a certain fraction of seed from the seed bank close enough to the soil surface to be exposed to dormancy-breaking conditions. Thus, one year of poor weed control can result in weed problems for years into the future.

In most cases, crops have had poisonous secondary compounds bred out of them. For example, the wild species from which tomatoes and potatoes originated have high levels of poisonous alkaloids. In many cases, weeds contain high levels of exotic, poisonous compounds. Although the exact function of most of these compounds is unknown, the majority of evidence indicates that they play a vital role in protection of weeds from pathogens, insects, nematodes, and herbivores. It is common to find very healthy weeds in fields of crops that have been ravaged by one or more microbial or animal pests. Thus, in the absence of insecticides, nematocides, and fungicides, weeds are usually more secure from these pests than the crop.

Significant physiological or biochemical differences between crops and weeds can be the basis for herbicide design. If an important biochemical site is more important to the weed than the crop, it may be an ideal herbicide target. However, there are no sites that are common to all weeds, but not to crops. There are herbicides that attack biochemical sites in monocots that are resistant in dicots (e.g., the aryloxyphenoxy propionates), and there are those to which dicots are extremely susceptible, but have little effect on monocots (e.g., 2,4-D). Many highly successful weeds have C_4 carbon fixation, whereas only a handful of crops have this type of carbon assimilation. However, despite significant effort, this site has not been successfully exploited by the herbicide industry.

B. Weed–Crop Interference

The density of weeds in a field required to reduce crop yield can be surprisingly small. This is partly because weeds are generally good competitors for water, light, and nutrients. Furthermore, in addition to reducing abiotic sustenance that the crop could use, weeds also can introduce undesirable, new factors to the field such as allelochemicals. Some weed species produce sufficiently phytotoxic allelochemicals to stunt the growth of competing plant species, including both the crop and other weeds. Such effects are often subtle and difficult to prove.

Understanding the effects of different levels of interference is important in determining potential crop losses and economic thresholds of weeds. The economic threshold can be defined as the weed density at which the economic loss justifies the expense of a weed management option (e.g., cultivation or a herbicide treatment). The decision is complicated by the fact that even a few weeds left in a field will generate large numbers of weed seed or other propagules that may cause problems in future crops. Thus, present and future interference must be predicted for the most effective weed management decisions. Furthermore, the effect of weeds on the quality of harvested crops is an almost unstudied aspect of weed science that should be understood in order to accurately determine economic thresholds.

C. Population Genetics and Ecology of Weeds

Compared to major crops and even some wild plants with no significant economic value, little is known of the genetics of weeds which cause the greatest economic damage. Within a given geographic area, the gene pool of most weed species is generally more varied than that of crops. Considering the weed's enormous reproductive capacity, this may give the weed population an advantage under a range of environmental and biotic stresses. For example, more than 200 weed species have evolved resistance to one or more herbicides. In some cases, resistance becomes predominant within three or four generations of weeds exposed to the herbicide. Some species become resistant to certain herbicides across wide, geographically isolated areas, demonstrating that these species are predisposed to become resistant to particular herbicides. For example horseweed (*Conyza* spp.) has become resistant to paraquat in the British isles, Israel, North America, Europe, Japan, and Australia. The interactions of plant biochemistry, physiology, and genetics which predispose certain species to become resistant to particular herbicides are not understood in any of the numerous examples of this phenomenon. Similarly, when biocontrol methods of weed control become more widely utilized, the population genetics of target weeds will play an important role in determining how soon resistance will occur.

The success of a weed species in any environment is due to a myriad of factors. In agricultural ecosystems consisting of a crop monoculture and associated weeds, predicting the success of particular weed species or understanding the shifts in predominant weed species is difficult. Factors such as competitive ability, stress tolerance, genetic diversity, reproductive modes, and susceptibility to weed management techniques all play roles. How these factors compare to the crop and competing weed species determines the success of a weed. The large number of weed species, each with wide but varying genetic diversity, insures that successful weed management agents or strategies are generally only temporary, lasting until a new weed species fills the voided agroecosystem niche or until the managed weed evolves to cope with the management system.

III. Nonchemical Methods of Weed Management

A. Cultural Methods

Before the advent of herbicides, cultural methods were the only techniques available for weed management. Weeds can be managed by manual cultivation (e.g., hoeing or pulling), by animal-drawn cultivators, or by mechanized means. Manual cultivation is not severely limited by weather conditions, is highly precise, and does not require skilled labor. However, in most of the developed world it is too expensive for economic agricultural production of agronomic crops. Mechanized cultivation for weed management is much more cost-effective. It may be made before, during, and/or after crop development. Problems associated with mechanized cultivation include soil compaction by heavy farm equipment, soil loss from wind and water, inability to cultivate during long wet periods, and highly efficient transportation of weed propagules to microenvironments suitable for dormancy loss and seedling establishment. [*See* PEST MANAGEMENT, CULTURAL CONTROL.]

In lawns and fields, mowing can effectively manage or eliminate unwanted vegetation of many weed species. Mechanical mowing or cutting with larger implements can be used to reduce understory weedy brush and vegetation from orchards, pastures, and other locations.

There is currently a trend to minimize cultivation in order to conserve soil and fossil fuel. Mulches are a cultural alternative to cultivation. In agronomic crops, only plant mulches are economically feasible. Cover vegetation used as mulch may be living or dead during crop production. For example, in temperate zones, winter ryegrass may be sown after crop harvest. In the Spring, it is generally killed with a herbicide before or during crop planting. Effective planting into untilled soil usually requires specialized equipment. Since no tillage is used, no new weed propagules are brought to the soil surface, and the dense mulch of living or dead vegetation suppresses or prevents the establishment of weeds from the propagules that might exist on the soil surface. Furthermore, survival of weed propagules on the soil surface, where they are exposed to climatic extremes and herbivorous animals, is significantly less than that in the soil. Some mulch species have allelopathic effects upon certain weeds, further enhancing their weed-suppressing activity.

In high value crops, such as many horticultural crops, plastic mulches have been used to economically suppress weeds. Plastic mulches suppress weeds by several mechanisms, including (1) providing a mechanical barrier; (2) preventing access to proper light quantity and/or quality; (3) creation of an unsuitable gaseous environment for seedling establishment; (4) enhancement of weed pathogen activity; and (5) raising the temperature to levels that kill weeds. Light transmittance (both quantity and quality), gas permeability, and mechanical strength of the mulche influence each of these mechanisms. The latter mechanism is termed solarization and is considered the most important means of weed suppression by plastic mulches.

The geometry of planting can greatly influence weed management. For example, when crop rows are planted closer together and/or more crop plants are planted per unit area, the crop will more rapidly compete effectively with weeds for sunlight than in widely spaced rows. Crops planted in elevated rows (ridges) can be cultivated (ridge tillage) more effectively under some circumstances.

Crop rotation generally aids in reducing weed problems. The weeds associated with different crops differ due to many factors. Thus, crop rotation reduces the soil seed bank of particular weed species during the years that a crop with which the weeds are incompatible is grown.

Fire can be used to manage weeds. Burning crop stubble after harvesting can reduce weed populations and destroy seed of some weed species. However, this method is illegal in some U.S. states. Hand-held or mechanized devices for directing flames to weeds have been used successfully in some settings for weed control. Electrocution of weeds with tractor-mounted electrodes has been researched, but not adopted commercially.

B. Biocontrol

Weeds have natural insect, pathogen, nematode, and herbivore pests, just as do crops. Those organisms that are specific for weeds can be turned against them. This approach can be divided into "classical" and "inundative" biocontrol methods. The classical approach is to introduce an exotic weed pathogen or insect that will propagate itself within the environment after it is unleashed. This strategy has been most successful when insects from outside the range of the weed are released. In cases in which the weed has not evolved defenses to the insect or pathogen and the biocontrol agent has no local enemies, there is an enhanced chance of success with this method. The classical approach is particularly appealing in settings in which the use of herbicides is prohibited by either economics or environmental concerns. For example, the *Opuntia* spp. cactus, a particularly onerous weed in the rangelands of Australia, was effectively removed as a significant problem by the introduction of the *Cactoblastus* moth. There have been similar successes with the classical approach in the rangelands and waterways of the United States. The classical approach has generally been a public sector effort, in that once the biocontrol agent is released, it is self-propagating and there is no opportunity for repeat sales of the biocontrol product. This approach is generally too slow for use in annual crops in which weeds must be rapidly and uniformly suppressed. [*See* PEST MANAGEMENT, BIOLOGICAL CONTROL.]

The inundative approach involves augmentation of the population of a natural enemy of a weed to numbers that can effectively manage it. Because these are indigenous organisms, they generally have natural enemies and the target weed has some tolerance to them. Thus, they usually dissipate with time, requiring reapplication every year. Microbial biocontrol agents lend themselves to this method, in that they can be produced, stored, and applied to weeds, much like chemicals. Three commercial mycoherbicides have been marketed in North America and several others are under development (Table I). Mycoherbicides may be applied as either mycelial preparations to the soil or spores to the soil or foliage.

The most common limitations to inundative microbial biocontrol agents are cost, short shelf-life, unpredictable efficacy, limited host range, and requirements for specialized application equipment. Although more than 200 potential mycoherbicides have been discovered, only four are commercially available, and there is little prospect that many more will be become available in the next decade. Further research on microbe strain selection and manipulation, storage formulation and stabilization, application formulation, application technology, and host range manipulation will be required before microbial herbicides can be expected to play a significant role in weed control.

Grazing and foraging animals (e.g., goats, geese, and pigs) have sometimes been useful in the biocontrol of weeds. Goats, in particular, will remove much of the unwanted vegetation from cattle and sheep pastures. In Australia, rotating sheep with wheat is an important component of weed control in both wheat and pasture. Pigs have been used to remove the tubers and rhizomes of perennial weeds from agricultural land.

TABLE I

Mycoherbicides That Have Been Commercially Available during the Past Decade or Have Been or Are under Development

Organism	Trade name	Target weed
	Commercially available	
Colletotrichum glocosporiodes[a]	Collego	Northern jointvetch (*Aeschynomene virginica*)
Phytopthora palmivora	DeVine	Stranglervine (*Morrenia odorata*)
Colletotrichum glocosporiodes	Luboa-2	Dodder (*Cuscuta* spp.)
Colletotrichum gloeosporoides	Biomal	Round-leaved mallow (*Malva pusilla*)
	Under development	
Alternaria cassiae	Casst	Sicklepod (*Cassia obtusifolia*)
Colletotrichum truncatum	Coltru	Hemp sesbania (*Sesbania exaltata*)
Colletotrichum coccodes	Velgo	Velvetleaf (*Abutilon theophrasti*)

[a] Different strains of *C. gloeosporoides* have distinctly different host specificities.

IV. Herbicides and Their Use in Weed Management

A. Herbicides and Their Modes of Action

Since the first synthetic, organic herbicide, 2,4-D, was introduced commercially after World War II, thousands of herbicides have been patented and hundreds have been marketed. The herbicide market is highly competitive, with continual improvements in selectivity, safety, and efficacy. The approval, registration, and use of herbicides is a highly regulated activity. The most desirable selectivity is for the herbicide to have no effect on crops, with a useful level of phytotoxicity on all of the major weeds in those crops. There is a trend toward development of herbicides with more biological activity per unit mass. These low use-rate compounds generally have one very specific molecular site of action that is unique to plants. [*See* HERBICIDES AND HERBICIDE RESISTANCE; PEST MANAGEMENT, CHEMICAL CONTROL.]

Herbicides can be classed by chemical family or by their mode of action (Table II). It has become increasingly important to understand the biochemical mechanism of herbicides. This information can be important in predicting toxicological effects, in designing more effective and selective herbicides, and in producing herbicide-resistant crops by biotechnology (see later).

There are thousands of potential biochemical sites in plants that could be targeted by a herbicide. Several million compounds have probably been screened for herbicidal activity, and, of these, several hundred have been commercialized, although many of these products are no longer on the market. The molecular sites of action of the majority of commercialized herbicides are known. Less than 20 molecular sites of action are represented. Thus, of the thousands of potential sites of action, only a small fraction are represented by commercially successful herbicides. This may be because only a few sites of action have the unique characteristics required for a good herbicide target or because organic chemists who have synthesized the majority of the compounds screened by the herbicide industry have generated a less diverse spectrum of

TABLE II
Modes of Action of Several Major Herbicide Classes

Mode of action (molecular site)	Chemical class of herbicide	U.S. tradename examples of herbicide class	Decade of first introduction
Auxin-type activity			
Site of action unknown	Phenoxypropanoic acids	2,4-D	1940s
Inhibition of amino acid synthesis			
Acetolactate synthase	Sulfonylureas	Glean	1980s
	Imidazolines	Scepter	1980s
Enolpyruvylshikimate phosphate synthase	Glyphosate	Roundup	1970s
Glutamate synthase	Glufosinate	Ignite	1990s
Inhibition of carotenoid biosynthesis			
Phytoene desaturase	Pyridazinones	Zorial	1970s
Exact site unknown	Isoxalidinones	Command	1980s
Inhibition of photosystem II			
D-1, quinone-binding protein	Triazines	Atrazine	1950s
	Nitriles	Buctril	1960s
	Substituted ureas	Lorox	1950s
	Anilides	Stam	1960s
Interference with microtubules			
Tubulin	Dinitroanilines	Treflan	1960s
Exact site unknown	Dithiopyr	Dimension	1990s
Inhibition of porphyrin synthesis			
Protoporphyrinogen oxidase	*p*-Nitrodiphenyl ethers	Blazer	1960s
Inhibition of lipid synthesis			
Acetyl CoA carboxylase	Cyclohexanediones	Poast	1980s
	Aryloxyphenoxypropanoates	Hoelon	1970s
Unknown	Acetanilides	Lasso	1960s
Inhibition of folate synthesis			
Dihydropteroate synthase	Asulam	Asulox	1960s
Inhibition of cellulose synthesis			
Exact molecular site unknown	Dichlobenil	Casoron	1960s
Generation of superoxide radical			
Photosystem I	Dipyridiliums	Gramoxone	1960s

compounds than required to discover other effective sites of action. This question remains to be answered.

Although most successful herbicides are the result of random screening of compounds for herbicidal activity, this discovery strategy is in a state of rapidly diminishing returns. Two new strategies are becoming more important: biorational design and using natural phytotoxins as templates for new herbicides. Biorational design is the process of targeting a specific molecular target in the weed. For example, inhibitors of a particular enzyme in the weed can be designed, based on detailed knowledge of the enzyme structure, substrate(s), product(s), and/or cofactors. Success of this strategy is partially dependent on adequate knowledge of the physiology and biochemistry of the weed. Natural phytotoxins offer new and unusual chemicals with proven herbicidal activity. Using these chemicals without modification or as templates for structure–activity manipulations that might improve their characteristics has become an important herbicide discovery strategy.

B. Herbicide Use

By unit mass, herbicides constitute 60 to 70% of all pesticides used in agriculture. In developed countries, more than 90% of the land on which all major crops are grown is treated with a herbicide at least yearly. Thus, herbicides have become the major tool for weed management in agriculture.

Herbicides are applied in several different ways. Before or during planting of a crop, they can be applied directly onto or incorporated into the soil. These practices can alleviate weed pressure during establishment of the crop stand. Later, herbicides can be applied directly over the emerged crop or between crop rows if the crop is susceptible to the herbicide (postemergence application). Postmergence applications can be made with many different types of spray systems (hand-held, tractor-mounted, or aircraft-mounted) or by rubbing the herbicide onto the weed foliage from a wax bar or rope wick impregnated with herbicide. Herbicides can also be applied in irrigation water (chemigation). In areas of high weed pressure, more than one of these methods, each with a different herbicide, is generally utilized.

In many situations, herbicides are sprayed in mixtures of two or more pesticides in order to minimize the number of trips over the field with mechanized or aerial spray equipment. Other herbicides or pesticides can decrease or increase the activity of a herbicide, depending on many factors. Without knowledge of potential interactions, either in the mixing tank or on or in the plant, tank mixing pesticides can result in poor performance of agrochemicals. Marketing premixed combinations of compatible or synergistic herbicides is a growing trend.

Formulation of herbicides can also strongly influence their weed-killing capacity. Adjuvants used with herbicides generally increase droplet spreading and decrease the rate of droplet drying on leaf surfaces. These effects, as well as others, have been implicated in their improvement of herbicide activity. The proper formulation for a herbicide is a function of the target weed species, the age of the weed, the herbicide, and climatic conditions. Not enough is known of how these factors interact in order to custom formulate a herbicide for a particular set of conditions. Such optimal formulations could greatly reduce the amount of herbicide needed for effective weed management.

Chemical safeners are used with some crops to protect them from herbicides that ordinarily could not be used with the crop. Most safeners act by enhancing the metabolic degradation of the herbicide in the crop. In almost all cases in which crops are naturally tolerant to a herbicide, the crop is tolerant through rapid metabolic degradation of the herbicide rather than due to resistance at the molecular target site.

In some cases, reduced tillage results in increased dependency on herbicides. Without tillage, herbicides can be the major alternative for weed management. Even with vegetative mulches grown during the fallow season, herbicides are often used to kill the mulch vegetation before or during planting of the crop.

C. Herbicide Resistance

Resistance to herbicides has evolved more slowly than insect resistance to insecticides for several reasons. These include the relatively long generation time of weeds, the long-lived soil seed bank, and the often intermittent nature of the selection pressure. Nevertheless, more than 200 weed species have evolved resistance to various herbicides and the problem is growing geometrically. In some cases the weed is resistant only to the herbicides that have been used on the fields in which it originated. In other cases, resistance extends to other herbicides with the same mechanism of action, even though the weed population may not have been exposed to these herbicides (cross-resistance). Occasionally, resistance is found to an array of herbicides with diverse mechanisms of action (multiple resistance). If the weed population has been exposed to all of these herbicides, multiple resistance can be the result of multiple mechanisms of resistance. If not, enhanced capacity to degrade or sequester a wide range of xenobiotics may explain multiple resistance.

D. Environmental and Toxicological Aspects of Herbicide Use

In developed countries, the largest volume of pesticides introduced into the environment is comprised of herbicides. Furthermore, many of these compounds are placed directly into the soil where they are readily mobile. It is not surprising that herbicides and herbicide breakdown products represent a major fraction of pesticides and pesticide-related compounds found in groundwater. Postemergence, foliarly applied herbicides can be leached into soil or into surface water. Herbicide sprays (particularly aerially applied) can drift onto nontarget crops and into nonagricultural areas (recreational, residential, etc.). Volatile herbicides become part of the atmosphere until sufficiently degraded. Any herbicide used in agriculture has the potential to contaminate food (either human or for animal feed) in the applied form and/or as degradation products. Considering the large amount of herbicides used worldwide, the potential for environmental contamination is significant if use restrictions are not carefully followed. The toxicological and environmental effects of current levels of contamination are a point of controversy.

Herbicide registration (approval for commercial use) and directions for use are highly regulated in the United States and most other developed countries. In general, the trend is toward more stringent registration and use restrictions. Tolerance levels (allowable concentrations) in food and water are set by the U.S. Environmental Protection Agency (EPA) for each herbicide. An allowable daily intake is also set for each herbicide and its degradation products. These levels are based on toxicology data, with a large safety factor built in. Nevertheless, large amounts of herbicides are used, and improving analytical capacities are making it possible to detect minute quantities of herbicides in our food and water. These previously undetectable levels of herbicides cause concern in some quarters, even though they are well below safety standards established by EPA.

Herbicide residues consumed by the average person in food and water are thought by many scientists to constitute a small fraction of the carcinogens in the food and water supply. At any level, probably only a small fraction of herbicides and their residues are carcinogenic. Other carcinogens–such as natural pesticides from plants, compounds from smoked, charred, or seared foods; toxins from spoilage microbes, nitrates, nitrites, and nitrosamines, and ethanol–are thought by many to play a more important role in disease development in humans. However, this is a controversial area in which absolute proof of cause and effect is extremely difficult.

Most of the data available indicate that herbicide residues have no direct long-lasting effects upon soil microflora. Vegetation changes caused by the herbicide are more influential in indirectly affecting soil biotica.

Current trends in herbicide use and regulation will mitigate future environmental effects of herbicide use. Most newer herbicides registered are low-rate use compounds that are less mobile in soil. Furthermore, they generally have short environmental half-lives. Some older, higher use rate herbicides will soon disappear from the market because of competition and/or increased regulatory pressures.

V. Weed Science in Integrated Pest Management

Like all ecosystems, agroecosystems are comprised of various biotic and abiotic components involved in complex interactions. Integrated pest management may be defined as pest management strategies which are designed with some knowledge of these interactions in order to minimize cost, both economic and environmental. [*See* INTEGRATED PEST MANAGEMENT.]

For example, rotation of crops is helpful in control of all crop pests because long-standing monocultures allow the buildup of populations of nematodes, weeds, insects, and pathogens that are injurious to the crop. Consideration of the effects of pesticides on nontarget organisms is important in integrated pest management. For example, herbicides can significantly influence susceptibility of crops to plant pathogens. In some cases, the crops are made more resistant to pathogens and in others their resistance is reduced. For example, glyphosate has been found to increase the susceptibility of some plant species to certain pathogens under some conditions by blocking the plant's biosynthetic machinery which produces antimicrobial compounds.

Weeds can be alternate hosts for crop-damaging nematodes or insects. Conversely, weeds can be hosts or habitats for beneficial insects. Little is known of such relationships and their role in crop production.

VI. Future Trends in Weed Management

A. Biotechnology and Weed Management

All crops are naturally resistant to some herbicides. However, they are not always resistant to herbicides that could offer valuable weed management tools for the crops. Plant breeders have spent little effort in developing cultivars resistant to new herbicides because of limited variability in crop germplasm and the possibility that, after a long and laborious breeding effort, the herbicide will disappear from the ever-changing herbicide market. With modern biotechnology, any crop can be made resistant to any herbicide relatively quickly.

The methodology has consisted primarily of cell selection or gene transfer techniques. Treating crop cell cultures with herbicides to select for natural mutations conferring resistance has resulted in several herbicide-resistant crops. This method does not require a biochemical knowledge of mode of action or degradation of the herbicide. An alternative method is genetic modification of the crop by genetic engineering. Foreign genes can confer herbicide resistance by introducing resistant sites of action or enzymes that degrade the herbicide. Examples of each method are provided in Table III. An example of a herbicide-resistant crop is depicted in Fig. 1.

Controversy exists regarding the environmental impact of herbicide-resistant crops produced by biotechnology. However, in most cases the herbicides to which these crops are being developed offer more environmentally benign choices than currently exist. Furthermore, they will provide management options to farmers that can be used with reduced tillage and no-tillage agriculture, thus, conserving soil and fuel. They also offer one of the few hopes for coping with

TABLE III

Herbicide-Resistant Crops Available or Currently under Development

Herbicide	Crop	Method[a]	Strategy[b]
Atrazine	Canola	M	Site
Bialaphos	Soybean, corn	B	Degrade
Cyclohexanediones	Corn	C	Site
Bromoxynil	Tobacco, cotton, potato	B	Degrade
Glufosinate	Tobacco, sweet potato, tomato, sugarbeet, oilseed rape, alfalfa corn, poplar	B	Degrade
Glyphosate	Poplar, soybean, tomato cotton, flax, sugarbeet	B	Site
Imidazolinones	Canola	M	Unknown
	Corn	C	Site
Sulfonylureas	Tobacco, corn, cotton	B	Site
	Canola	C	Site
2,4-D	Tobacco	B	Degrade
	Cotton	B	Degrade

Note: Partial listing of research and development of herbicide-resistant crops by industry.

[a] B, gene transfer by biotechnology; M, microspore mutagenesis and selection; C, cell selection.

[b] Site, site of action; Degrade, enzyme(s) for degradation of herbicide.

parasitic weeds which drastically reduce crop yields in Africa. [*See* PLANT BIOTECHNOLOGY: FOOD SAFETY AND ENVIRONMENTAL ISSUES.]

Genetic modification of microbial weed control agents by biotechnology could solve some of the problems in development of effective microbial herbicides. Such manipulation could allow the development of mycoherbicides and bacterial herbicides with more desirable host ranges and improve virulence. However, without proper safeguards, such modified plant pathogens could cause harm to crops or other important plant species.

Ultimately, molecular biology will be used to make crops more competitive with weeds. However, this will be a difficult task in that competitive ability is a complex, multigenic trait, and imparting certain aspects of competitiveness may conflict with other desirable traits such as crop yield.

B. Weed Management in Organic Farming

Organically-grown foods are generally defined as foods produced without using synthetic fertilizers or pesticides. This eliminates the use of synthetic herbicides for weed management, leaving only natural herbicides, biocontrol, and cultural methods for weed control.

FIGURE 1 The response of a nonselected line (left) and two corn lines (middle and right) selected for resistance to sethoxydim, a grassy weed herbicide, at 0.44 kg sethoxydim/ha. These plants were regenerated from sethoxydim-resistant or nonselected callus cultures. The photographs were taken approximately 10 days after treatment with the herbicide. (Courtesy of David A. Somers, Department of Agronomy and Plant Genetics, University of Minnesota.)

Natural compounds are intrinsically no more safe than synthetic ones. The most potent toxins known are natural compounds. Nevertheless, by some definitions, organic foods can be produced with the use of natural toxins as pesticides. Two toxicologically safe natural compounds, bialaphos and phosphinothricin, are commercially available as herbicides. Bialaphos is a fermentation product of *Streptomyces viridochromogenes* that is effective on a broad spectrum of weeds. It is currently available only in Japan and other Asian markets. To be herbicidally effective, bialaphos must be broken down in the plant to phosphinothricin. Phosphinothricin is synthetically produced and sold throughout most of the world as the herbicide glufosinate. Although synthesized glufosinate is chemically identical to the natural product phosphinothricin, it might not be considered as a component of organic farming by organic farming purists.

C. New Technology and Weed Management

Empirical models or "expert systems" are under development as aids for farmers in making decisions affecting weed management. With the paper data input (e.g., weed species, weed density, weed and crop development stage, climatic conditions, expected price of the harvested crop, and herbicide prices) the computer model produces a range of weed control options with estimated return on the investment. When perfected, such management tools will allow maximal efficiency and minimal environment impact of weed management actions.

Only a small amount of herbicides sprayed into the environment reach target weed species. This is due to a number of factors, including drift of spray particles away from the target and the fact that the spray equipment cannot differentiate between target species and other plant species or bare ground. Spray equipment has been recently developed which will differentiate between vegetation and bare ground, spraying only when vegetation is detected. If a field is 25% covered by weeds before planting, this spray system can potentially reduce the amount of herbicide needed by 75%. This equipment can be used to treat weeds between crop rows with nonselective herbicides or to spray all of the vegetation in a field with crops that are resistant to the herbicide.

It is technically feasible for a miniature television camera to capture the image of a plant, for a computer to analyze the image and identify the species, and for the computor to actuate a spray system to treat identified weeds with the appropriate herbicide. Such a system could greatly increase weed management efficiency and safety by greatly reducing the amount of herbicide needed for a high level of weed control. The low speed, insufficient reliability, and high cost of such a system would be unacceptable at present. However, rapid advances in electronics and engineering will probably make such a system practical within the next decade.

D. Potential Impacts of Global Climate and Atmospheric Changes on Weed Management

Global climate change will affect agriculture, as crop production is intrinsically linked to climate. As mentioned earlier, weeds generally tolerate climatic stress better than the crops with which they associate themselves. In some geographic areas, climatic change in the form of increased drought stress, ultraviolet radiation, and temperatures will give weeds an advantage over crops. Air pollution (SO_2, ozone, etc.) is harmful to both crops and weeds. Little is known of relative tolerance of crops and associated weeds to these stresses. [*See* AIR POLLUTION: PLANT GROWTH AND PRODUCTIVITY.]

The carbon dioxide enrichment of the atmosphere that has occurred during the past century enhances the growth of all plants. However, it favors C_3 plants (generally dicots) more than C_4 plants (generally monocots such as grasses). This trend should favor many dicot weeds (e.g., velvetleaf) over C_4 monocot crops such as corn. Conversely, C_4 weeds in C_3 crops (e.g., johnsongrass in soybeans) should become less competitive.

As climate and the atmosphere change, shifts in predominant weed species and/or ecotypes of species can be expected. Just as there are varieties of most major crops that can be grown in a wide range of climates, there are weed species that are most adapted to each climate. In some areas there have been profound changes in the weed species with certain crops during this century. These changes can be linked to use of certain herbicides in some cases; however, in others, there is no clear reason for the shift in vegetation. Whether the climate or atmospheric changes that have already occurred are involved is unknown.

E. Weed Control in a More Stringent Regulatory Environment

In most countries the toxicological and environmental regulations governing pesticides are becoming increasingly stringent. This is leading to safer herbicides, but is escalating costs of commercializing new products. Fewer companies are engaging in herbicide development and fewer new herbicides are being introduced. In the United States, older pesticides that were registered for use at a time when regulatory requirements were less strict are in the process of being re-registered, using current regulatory requirements. This process will lead to the loss of availability of many older herbicides.

In major crops, there is little likelihood that these trends will drastically impact chemical weed control in the next decade. However, they have already greatly limited the availability of inexpensive chemical weed control in minor crops, many of which are horticultural crops. The herbicide industry can no longer afford the cost of registration or re-registration of some herbicides for many minor crops. Weed control in such crops is now generally much more expensive than in major agronomic crops.

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Wetlands and Riparian Areas: Economics and Policy

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Glossary

Circular 39 wetlands Classification developed by the U.S. Fish and Wildlife Service in 1954 that distinguishes between coastal and inland areas of fresh and saline wetlands, deriving 20 wetland types on the basis of water depth and vegetation within these four broad categories

Cowardin system wetlands Named after its developer, this classification includes both wetlands and deepwater habitats grouped in a hierarchical structure on the basis of hydrologic, geomorphologic, chemical, and biological factors; five major systems (marine, estuarine, riverine, lacustrine, and palustrine) form the first level in the hierarchy, further subdivided into subsystems based on the degree of inundation and dominance of vegetative types

Externalities Unavoidable joint product of an economic production process that may produce goods or evils, enjoyed by, or inflicted on, society at large

Farmed wetlands Wetlands that have been cleared, drained, or otherwise manipulated to make cropping possible, but still meet jurisdictional wetland definitions

Hydric soils Soils that are saturated, flooded, or ponded long enough during the growing season to develop anaerobic conditions that favor the growth and regeneration of hydrophytic vegetation; hydromorphology characteristic of hydric soils includes development of gray mottles or matrix, organic streaking, and manganese or iron oxide nodules or concretions

Hydrophytic vegetation Vegetation that is adapted for growth in saturated soil conditions; biologists divide hydrophytic vegetation into several classes, including obligate, facultative-wet, and facultative species that always, primarily, or equally often appear in wetlands

Jurisdictional wetland Wetlands defined and delineated according to one or another of Agency or Interagency Manuals for Identification and Delineation of Wetlands issued in 1987, 1989, or 1991 for the purpose of administering Section 404 of the Clean Water Act or the so-called swampbuster provision of the 1985 Food Security Act

Wetlands farmed under natural conditions Open wetland that dries out adequately in normal years to plant and harvest a crop

Wetlands and riparian areas are areas intermediate between land and water. Since 1977, the Federal government has used a three-part definition involving hydric soils, hydrophytic vegetation, and hydrology. According to the U.S. Army Corps of Engineers (COE), which administers Section 404, wetlands are "areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions." The phrase "under normal circumstances" has been interpreted to mean that an area with wetland hydrology and hydric soils is still a wetland, even when adapted vegetation has been removed to make areas suitable for farming. Delineating wetlands has been controversial because of conflicts between landowners who want to use and develop these areas and environmentalists who want to preserve them.

I. Definition and Delineation

Controversy over wetland definitions has a long history, paralleled by evolving views on the need for government regulation of wetlands. Farmland does not correspond with the general public's image of wetlands, but may be treated as wetlands by the two programs that most directly affect private landowners: The Clean Water Act's (CWA) Section 404 permit program and the Food Security Act's (FSA) swampbuster provision. The U.S. Fish and Wildlife Service (FWS) developed the first federally applied wetland delineation method that considered vegetation and hydrology in 1979. In 1987, USDA, COE, and EPA developed manuals using a three-part wetland definition that considered soils, vegetation, and hydrology for their programs.

Concern that important wetlands were not covered under Section 404 and that all four Federal agencies with wetland programs were using different wetland delineation procedures led to development of the Federal Interagency Manual for Identification and Delineation of Wetlands in 1989. While some critics of the 1989 manual claimed that it expanded the area under Section 404 jurisdiction, there is no clear evidence that an expansion occurred because the area defined as wetland under varying definitions has never been estimated.

Before 1989, COE did not consider areas previously cleared for crop production as wetlands subject to permit requirements. The 1989 Manual delineated as wetland farm fields that had hydric soil if they had sufficient wetland hydrology to support hydrophytic vegetation if left undisturbed. COE reinterpreted the "normal circumstances" language of their definition to include situations where wetland vegetation, including trees, had been cleared for agricultural production. The 1989 manual also delineated as wetlands land whose soils are saturated within 18 in. of the surface for only 7 days during the growing season. These interpretations created problems with a variety of drier altered, artificial, or managed wetlands, and were at odds with the general public's image of a wetland.

An impression that wetland area had been expanded could have resulted from maps of hydric soils used to show areas that could potentially be wetlands. Presence of hydric soils is definite evidence that an area developed under saturated conditions. However, drainage for farming or other development alters the hydrology of a site with hydric soils, removing it from any wetland delineation. The 1989 manual required that an area have hydric soils and wetland hydrology.

A backlash against the 1989 manual developed as areas previously not considered wetlands became subject to permit requirements. Attacks by a coalition of farm, development, and utility company interests resulted in legislation introduced in the House to reform wetland regulation by changing the 1989 definition. Under this pressure, a revised wetland delineation manual was proposed in August 1991. Important differences between the 1989 and 1991 manuals are outlined in Table I. The 1991 manual requires that all three criteria be present at least some time in the year in order for a site to be a wetland. How many days and to what degree a site must be flooded to be a wetland are particular points of difference between the 1989 and 1991 manuals. Indicators of wetland hydrology are restricted and secondary indicators require corroborating evidence. There are differences in the way the growing season is defined in the two manuals, as well as differences in the methods that can be used to determine presence of hydrophytic vegetation. Special procedures are outlined for sites that have been disturbed, including farmed wetlands. Other procedures are used for "difficult-to-identify" wetlands that focus on which of the three criteria is difficult to determine. Finally, because of the growing controversy, the 1991 manual got far greater public notice and public comment than the 1989 manual.

Field tests of the 1991 and 1989 manuals by Federal, joint Federal and State, and State field teams under a variety of conditions indicated that 30 to 80% of land delineated as wetlands in the 1989 manual were excluded by the 1991 manual. Areas that would have been excluded include cottonwood and willow wetlands in riparian areas of the Rocky Mountains and Southwest, most bogs in the Northeast and Midwest, and many prairie potholes in the Dakotas. Also excluded would be high coastal marsh along the Pacific coast, some of the Florida Everglades in the National Park and remaining on private land, and as much as 80% of the Great Dismal Swamp in Virginia and North Carolina.

By January 1992, the 1991 delineation manual received more than 80,000 formal comments. Attempts to revise the manual to account for the diverging views bogged down. Funding for a National Academy of Science (NAS) study of the delineation question was included in EPA appropriations in 1993 that delayed any decision on delineation for 18 months. In the interim, COE and EPA have returned to use

TABLE I
Comparison of 1989 and 1991 Wetland Delineation Manuals

Item	1989 Manual	1991 Manual
Evidence of three parameters: hydric soils, hydrophytic vegetation, and wetland hydrology	Hydrology could be assumed from vegetation and soils; vegetation could be assumed from soils and hydrology	Independent indicators of all three required unless site is disturbed or a playa lake, prairie pothole, vernal pool, pocosin, or other special wetland
Duration of inundation or saturation	Seven or more days during the growing season	Inundated 15 or more consecutive days or saturated to the surface 21 or more consecutive days during the growing season
Depth of soil saturation	Saturated within 6–18 in. of the surface, depending on soil type	Saturated to the surface as indicated by water that can be squeezed from surface soil
Acceptable indicators	Lists strong and weak indicators of hydrology, including presence of hydric soils	Lists primary and secondary indicators of hydrology; only primary indicators can be used without corroborative information; eliminates presence of hydric soil as an indicator of hydrology
Definition of growing season	Based on growing season maps delineated by soil temperature regimes	Based on local weather data indicating 3 weeks before last spring killing frost and 3 weeks after last fall killing frost
Hydrophytic vegetation criterion	Under normal circumstances, based on composition or a prevalence frequency analysis	Under normal circumstances, based only on a prevalence frequency analysis
Public input	Notice and public comment rulemaking not required	Formally proposed in the *Federal Register*; public comment not required, but solicited

of the 1987 delineation manual. President Clinton's August 1993 wetland policy statement affirmed use of the 1987 delineation manual pending completion of the NAS study. The President's statement also gave USDA responsibility for all wetland delineation on agricultural lands, but details about how this arrangement will be worked out within existing COE and EPA authorities remain to be specified. USDA never formally adopted the 1989 manual and is still running the swampbuster program under regulations first issued in 1987.

II. Current Extent

A. Wetlands

While no estimates of wetland extent using jurisdictional definitions have been made, various estimates and inventories using scientific definitions have been made over the years. According to the 1987 National Resources Inventory (NRI) there were 83.2 million acres of rural nonfederal wetlands in 1982. These are wetlands defined by the older Cowardin wetland definition based primarily on hydrology and used by the FWS. This definition excludes many acres of farmed wetlands included in current jurisdictional definitions. Eighty-three percent of nonfederal wetlands inventoried were privately owned, with the remainder in State (13%) and local (2%) government ownership or on Indian tribal lands (2%). "Wetland" is neither a land use nor a land cover, but a condition prevailing in many rural land uses. More than half of all nonfederal wetlands were forested. The second largest land cover category (20.9%) was "other lands," a residual category. About 17% of wetlands were in pasture and range. Only 5.6% of wetlands was in crops. Not inventoried in the NRI were an estimated 12.5 million acres of wetlands on Federal land, excluding Alaska.

Both farmed wetlands and wetlands farmed under natural conditions, as well as undisturbed natural wetlands, are subject to swampbuster provisions. Cropland on hydric soil that was once wetland but had been converted before 1985 is termed "prior converted" wetland and is exempt from swampbuster provisions. An example of farmed wetland is cleared bottomland fields in the lower Mississippi alluvial plain that flood over winter but are dry in time for spring plantings of soybeans or other crops. An example of wetlands farmed under natural conditions is the prairie potholes of the Northern Plains, shallow depressions of glacial origin that collect snowmelt and spring runoff but are dry enough to plant wheat in most years. A landowner cannot further drain or otherwise alter the hydrology of these wetlands to plant a crop without losing farm program benefits. Farmed wetlands and wetlands farmed under natural conditions are not pristine natural ecosystems, but they do continue to perform valuable natural functions. For example, prairie pothole wetlands provide important waterfowl feeding and nesting areas and bottomland wetlands provide waterfowl wintering areas and nursery areas for fish and invertebrates which fish feed upon.

There is no reliable estimate of the total farmland acreage subject to swampbuster and Section 404, but available data indicate some realistic limits. All 83.2 million acres of wetland inventoried in the NRI is subject to swampbuster provisions, but only 7% (5.7 million acres) was rated by USDA Soil Conservation Service technicians as having high or medium potential for conversion to cropland and thus has some likelihood of creating a violation. In addition to land inventoried as wetland, 53 million acres of nonwetland cropland on hydric soils can be identified from the NRI. More than half of this land (30 million acres) had no drainage. Half of that (17.9 million acres) needed drainage or other conservation practices for improved crop production. The remaining land was drained to some degree, but 4.5 million acres was not adequately drained for best crop production. These 53 million acres of cropland converted prior to 1985 are excluded from swampbuster provisions and COE agreed to exempt them from Section 404 permit requirements in 1990, a decision confirmed by regulation as part of President Clinton's wetland plan in 1993 (Table II).

When the 1989 interagency delineation manual was first introduced, some COE field staff did not distinguish between prior converted wetlands, farmed wetlands, and wetlands farmed under natural conditions. Complaints from farmers prompted the COE leadership to clarify the manual's three-part definition, stressing that a site ". . . effectively and legally drained to the extent that it no longer meets the regulatory wetlands hydrology criteria . . ." is not subject to Section 404. Staff were cautioned not to determine hydrology solely on hydric soil characteristics. In a memorandum issued in July 1990, the COE reiterated that normal practices are exempt from Section 404 (see below). Note, however, that substantial changes in land use, either to a more intensive agricultural use or to a developed use, are not considered normal practice. Coincident with President Clinton's wetland policy statement in 1993, the COE and EPA formalized guidance exempting 53 million acres of prior converted agricultural land from Section 404 jurisdiction. These actions completed a movement toward more consistent Federal wetland policy because both swampbuster and Section 404 were now using very similar wetland definitions.

Normal Farming Activities Are Exempt
from Section 404 Permit Requirements of the Clean Water Act

Certain activities conducted by farmers in agricultural wetlands are exempt from Section 404 requirements, and do not require notification or application to the Corps of Engineers for a Section 404 permit. These include:

Plowing
Seeding
Harvesting
Cultivating

These activities can be conducted on prior converted wetlands, farmed wetlands, and unaltered wetlands under natural conditions. The activities must be part of an ongoing farming operation, and cannot be associated with bringing a wetland into agricultural production or converting an agricultural wetland to a nonwetland use.

Other activities are exempt, providing woody vegetation is not removed and existing drainage is not modified. These include:

Drainage system maintenance
Construction of
Farm ponds
Irrigation ditches
Farm roads
Cropping hay or pastured wetland fields
Maintenance of
Farm ponds
Irrigation ditches
Farm roads

Specific exemptions were developed for troublesome, locally occurring practices, such as construction of rice levees in crop rotations.

B. Riparian Areas

Riparian areas are transition zones between aquatic and upland ecosystems with several characteristics

TABLE II
Wetlands and Hydric Cropland, United States, 1982

	Thousand acres	Percentage of wetlands
Rural, nonfederal wetlands	83,212	100
Potential for cropland	78,516	94
No conversion potential	42,639	51
Unlikely and other	30,177	36
High or medium potential	5700	7
Cropland	4696	6
		Percentage of hydric cropland
Cropland on hydric soil	53,137	100
Not drained	30,244	57
Needs drainage for farming	17,888	34
Drained	22,892	34
Not adequately drained	4468	8

Source: 1982 and 1987 National Resources Inventories.

that distinguish them from adjacent uplands. Natural riparian vegetation is adapted to high soil moisture. Riparian areas require high water tables or periodic flooding to maintain their natural vegetation. There is also a high degree of exchange between the aquatic and terrestrial systems: flooding from the streams brings nutrients to the terrestrial vegetation, while debris from the terrestrial vegetation is a food source for aquatic species. Riparian areas are generally more productive than upland areas, producing more biomass and maintaining a greater diversity of plant and animal species. Vegetative productivity and diversity make riparian areas excellent habitat for fish and wildlife species, and highly valued for livestock grazing.

Because of their proximity to water, riparian areas have been attractive sites for agricultural, residential, commercial, and industrial development. As a result, they have undergone dramatic alterations from their original state. Loss and alteration of riparian areas have occurred because of dam construction, channelization, and agricultural development. Livestock grazing is a major factor impacting many riparian areas.

While riparian areas serve important agricultural and ecological functions, there are surprisingly little data available describing their extent and location. The term "riparian" is used in several different contexts, ranging from all land in the flood plain to specific woodland habitats along streambanks. The term "riparian" has no official or regulatory meaning. One useful definition of riparian areas is land within the 100-year flood plain plus land along natural streambanks as riparian land. Data on land use or vegetation within riparian areas, which is of key importance for assessing agricultural and wildlife values, are less available than information on total area. Based on potential vegetation types, the original extent of riparian forest ecosystems has been estimated at 67 million acres. Including narrower cold water stream valleys and intermittent streams, increases the original extent to a range of 75 to 100 million acres, of which only 23 million acres remained in forested riparian ecosystems, excluding Alaska, by 1970. The 1977 and 1982 NRI inventories, respectively, estimated 52 million acres and 55 million acres of nonfederal, forested, flood prone land. However, much of this land is in pine plantations and other altered forest habitats. As much as 70–90% of all original forested riparian ecosystems in the United States have been eliminated through land use change.

1. Federal Riparian Land

Data on federally owned riparian land are sparse and of dubious reliability. Of the 175 million acres of public land in the Bureau of Land Management's (BLM) coterminous jurisdiction in 1985, only 903,000 acres (0.5%) was estimated to be riparian land. Riparian acreage increased 73% from 523,000 acres in 1977, when these estimates were first published, but had been as high as 941,000 acres in 1984. These changes are possibly due to changing floodplain definitions and reflect improvements in BLM reporting procedures. Over the same period, estimated miles of fishable streams remained relatively constant at about 20,000 miles. Oregon has the largest amount of BLM riparian area and the most stream miles, but Montana and Wyoming have riparian acreages almost as large, with proportionally fewer stream miles.

The Forest Service controls 187 million acres in the National Forest System. Of this, it is estimated that 2.3 million acres are riparian lands and wetlands, with 84,000 miles of fisheries streams. Only 65,000 acres of BLM riparian habitat was being managed in fiscal year 1977, and more than 440,000 acres were identified as being in unsatisfactory condition. Little information beyond these bare statistics is available for federally owned riparian areas. While public land managers have been working to improve conditions on many sections of federal riparian rangeland, successful projects represent only a small portion of such land in poor condition.

2. Nonfederal Riparian Land

A total of 56 million acres of frequently flooded land, a useful proxy for riparian land, was estimated in the 1982 NRI. Lands with a flooding class of "frequent" are defined as having more than a 50% chance of flooding in any year, or more than 50 times in 100 years. Almost 92% of rural nonfederal riparian lands were privately owned, while about 7% were controlled by state and local governments. Private riparian areas were predominantly forested (46%) with the remainder about equally divided between cropland, pasture and rangeland, and other uses. About 60% of state-owned riparian areas were in other nonagricultural uses, with the remainder split between forest and agricultural covers. Eighty% of Indian-owned riparian areas were rangeland or barren.

Agricultural uses accounted for almost 40% of rural nonfederal riparian land in 1982 (Table III). Almost all cropland was used for crop production. Livestock grazing accounted for 86% of pasture land and 94% of range in riparian zones. Most of the remainder was idle, but 2% was used for wildlife or recreation purposes, mostly in state or local government ownership. Wood production was the principal use for 94% of forested riparian areas, but only part of this was actively managed for timber production. Almost 3% of forested riparian areas were set aside for wilderness, wildlife, or recreation uses. The cover on more than 1 million acres of other nonagricultural land in riparian areas that was designated for wildlife and recreation uses cannot be determined from the NRI categories, but may also have been in natural or relatively undisturbed vegetation. Overall, protected uses such as state or locally controlled wildlife sanctuaries, wilderness areas, and recreation areas made up 4% of rural nonfederal riparian zones.

Developed uses were a small (less than one percent) part of riparian areas, but most developed uses in flood prone and natural streambank areas were excluded from the NRI because they were located in urban areas. Land that was idle or whose use could not be determined constituted 15% of rural nonfederal riparian area, reflecting the residual nature of much riparian land.

TABLE III

Land Cover and Land Use of Rural Nonfederal Riparian Areas, United States, 1982

Land use	Crop land	Pasture land	Range land	Forest land	Other land[a]	Total
			Thousand acres			
Agriculture	7753	6108	7026	699	0	21,586
Crops	7680	0	0	0	0	7680
Grazing	73	6108	7026	699	0	13,906
Wood production	0	0	0	23,563	0	23,563
Developed uses[a]	3	31	5	9	115	162
Wild areas[b]	19	123	178	728	1196	2,244
Idle[c]	251	804	270	129	7022	8476
Total[d]	8033	7067	7480	25,127	8333	56,040

Source: 1982 National Resources Inventory.

[a] Includes residential, commercial, industrial, institutional, transmission, waste disposal, transportation, military, and research uses.

[b] Includes designated wilderness, designated wildlife, designated wildlife study, and designated recreation uses.

[c] Includes idle land and land for which no use could be determined.

[d] Detail may not add to totals due to rounding.

3. Riparian Wetlands

Riparian areas are sometimes treated as synonymous with wetlands, particularly in arid parts of the West. While there is overlap, riparian areas are more extensive than riparian wetlands. Riparian wetlands are listed among the 10 most critical wetland problem areas by the U.S. Fish and Wildlife Service. Threats to these wetland systems include conversion to cropland, overgrazing, dam construction, and groundwater pumping that lowers water tables and drys up riparian wetland areas.

The 1982 NRI inventoried 144,000 nonfederal acres identified as riverine wetland systems across the United States, almost all of which are included within riparian land (Table IV). Riparian lands accounted for about 37% of rural nonfederal wetlands inventoried in the 1982 NRI. In addition to the riverine wetlands, almost all estuarine wetlands, about one-third of palustrine (upland) wetlands and 1/10th of lacustrine (lake shore) wetlands were located in riparian zones. However, 48% of frequently flooded lands were not wetlands as classified by the FWS's Cowardin system. Thus, a substantial upland component of riparian areas should be considered for management in addition to that area classed as wetland.

Eighty percent of the wetland riparian area was classed palustrine, a slightly smaller proportion than for all wetlands. More than 60% of all wetlands in riparian zones were forested and this land cover accounted for about three-fourths of riparian palustrine wetlands. Most of the other wetland types, including riverine wetlands, were inventoried in other nonagricultural land covers. For example, land cover on all riverine wetlands was barren land in the "other" category. Only about 20% of riparian pasture and rangeland was wetland, classed predominantly as palustrine.

III. Wetland Values

Perceived values of wetlands in North America have increased rapidly over the past two decades. Intrinsic wetland characteristics were often unrecognized or undervalued relative to values from conversion of wetlands to other land uses. For most of our history, we did not appreciate the benefits produced by wetlands because we did not understand enough ecology, biology, and hydrology. Our forefathers perceived only disease, foul odors, and wild animals in swamps and marshes and sought to "reclaim" them. Scientists today, recognizing how many different species and functions depend on wetlands, strive to increase our awareness of their ecological and environmental importance. Wetlands are the site of processes that produce social values: fish and wildlife values, like spawning areas for fish and duck breeding habitat; ecological services, like water quality improvement and flood peak storage; and economic values, including marketable commodities, like furs or wild rice, and nonmarket goods, like recreation (Table V).

The table below illustrates some of the bioeconomic linkages found in wetlands. To start, a wetland generates a function that produces a good or supports a service. Techniques are needed for estimating the economic value of wetland services which account for complex bioeconomic linkages. For example, the wetland may be a physical medium for tree growth that supports a service, such as commercial tree harvest. That service has an economic value, in this case

TABLE IV

Land Cover and Wetland Status of Rural Nonfederal Riparian Areas, United States, 1982

Land use	Crop land	Pasture land	Range land	Forest land	Other land[a]	Total
			Thousand acres			
Not wetland	7255	5372	6120	7475	1160	27,382
Palustrine	779	1694	979	17,652	1839	22,942
Estuarine	0	0	381	0	5005	5386
Lacustrine	0	0	0	0	173	173
Riverine	0	0	0	0	136	136
Marine	0	0	0	0	21	21
Subtotal	799	1694	1360	17,652	7173	28,658
Total[b]	8033	7067	7480	25,127	8333	56,040

Source: 1982 National Resources Inventory.

[a] Detail may not add to totals due to rounding.

TABLE V
Illustrative Wetland Functions and Estimated Values

Function	State and wetland type	Value per acre
		Dollars per acre
Fish and wildlife		
Mammal/reptile	Louisiana coastal	12
Fish/shellfish	Louisiana coastal	32–66
Waterfowl	Massachusetts coastal marsh	167
General	Michigan coastal marshes	843
Ecological services		
Sediment accretion	Georgia river	3
Flood control	Massachusetts river	362
Water quality	Georgia river	1108
Waste assimilation	Virginia tidal marsh	6225
Life support	Georgia river	10,333
Market services		
Fish production	Virginia tidal marsh	269
Timber production	Georgia river	1605
Aquaculture	Virginia tidal marsh	872–2241
Nonmarket services		
Education/research	Louisiana coastal	6
Waterfowl hunting	Mississippi bottomlands	12–17
Recreation	Massachusetts river	38
Recreation	Louisiana coastal wetlands	45
Recreation	Florida estuary	76
Historic and archeological	Louisiana coastal	323

the net value of the timber. Foresters can model and value linkages between site characteristics and tree growth, determining the types of trees that will grow on a site and the associated boardfeet of timber that can be produced. Next, the good or service must be valued in economic terms. Forest economists use market valuation techniques which consider commercial prices of timber, transportation costs, production costs, and other factors to estimate the net economic value of the timber produced.

Wetland	Forestry	Fisheries	Recreation
Function	Tree habitat	Fish habitat	Wildlife habitat
Service	Commercial timber harvest	Commercial fish harvest	Recreational waterfowl harvest
Value	Net economic value of timber	Net economic value of commercial fish	Net economic value of hunting success

In the example of commercial fishing, the linkages are less clear, particularly the relationship between fish habitat and commercial fish harvest. A wetland area functions as a nursery ground for young fish, and as a medium for further growth. The tonnage of fish and shellfish that can be harvested in an estuary, or offshore from the estuary, is related to this wetland habitat function, among other things. The economic value linkage is the relationship of the commercial fish harvest to the net value of the commercial fish species. That is, once the tonnage harvested is known, an economist can combine dock prices with estimates of production and harvesting costs to estimate the net economic value of the harvest.

Finally, the linkages that are least clear are those involving nonmarket valuation. For example, the wetland function could be wildlife habitat that provides a service of recreational waterfowl bag for hunters. Estimating the relationship between wildlife habitat and waterfowl bag is an extremely complicated process. The economic valuation linkage is the relationship between recreational waterfowl bag and the net economic value of hunting success. Nonmarket valuation techniques, such as the contingent valuation method, the travel cost method, or hedonic pricing, can be used to establish the linkage between the service and wetland values. The relationships between wildlife, wildlife populations, waterfowl bag, and economic values involve biological, recreational, sociological, and economic considerations.

While some of the values illustrated in Table V are impressive, most of them have been arrived at by economists using nonmarket valuation techniques. Even the market goods, such as fish production, timber production, and aquaculture, are not generally produced directly in the wetland, but indirectly because the wetland exists. Wetlands are typical of an economic phenomenon called externalities. Services produced by a wetland, such as wildlife habitat and flood control, are available to everyone in its vicinity, regardless of such concepts as property rights. But wetlands give least to their legal owner. The paradox of prodigious wetland output is that the wetland owner has very little ability to charge others for the services the wetland produces. The owner cannot gain from the wetland except by destroying it to accommodate some other use of the land.

IV. Wetland Conversion for Agriculture

A. Trends in Wetland Conversion

Despite controversy over wetland delineation, several sets of more or less reliable data provide insight into overall trends. The earliest wetland inventories treated all wetlands the same, describing them with such terms as "swamp and overflowed lands." These terms were adequate when the object of the inventories was to quantify how much land was unfit for crop production without drainage efforts. As wildlife management became an object of wetland inventories, a management-based classification was adopted by the FWS and published in their Circular 39. For the National Wetland Status and Trends Analysis, FWS commissioned the Cowardin system, a new classification system designed to capture ecologically important differences and segregate dissimilar wildlife habitats that are geographically separated. Neither of the systems used for management or scientific wetland inventories precisely matches any of the jurisdictional wetland definitions used in regulatory programs. Thus, there is no accurate, comprehensive accounting of wetlands subject to Section 404 or the swampbuster provisions.

The FWS estimates that in 1780 there were 392 million acres of wetlands in what now constitute the 50 United States, and 221 million acres of wetlands in the lower 48 States. By 1980, only 274 million acres remained, with only 104 million acres in the lower 48 States. This amounts to a 53% loss over 200 years, or an average annual loss of 585,000 acres.

USDA conducted drainage inventories to identify lands suitable for drainage and assess the agricultural potential of remaining wetlands. In 1906, 79 million swampland acres (excluding Alaska) were thought to have farm potential, but two-thirds of this was not fit for cultivation unless drained and cleared. A more comprehensive inventory in 1919 showed 91.5 million acres unfit for crops without drainage, but judged that only 75 million acres could ever be developed for agriculture. The American Society of Agricultural Engineers conducted a similar drainage survey in 1946–1948 that identified 97 million acres of wet, swampy, or overflow lands. However, they judged only 20 million acres could be drained for farming at reasonable cost. A related 1948 estimate by the Soil Conservation Service showed 20.7 million acres physically feasible to drain and develop for agriculture.

The FWS, cooperating with State fish and game departments, conducted the inventory published as Circular 39 in 1954. For the first time, this inventory focused on managing wetlands, rather than eliminating them. It counted a total of 74.4 million acres in the 20 wetland types listed in Circular 39. The National Wetland Status and Trends Analysis was conducted by the FWS in 1979 to not only identify current wetlands according to the Cowardin system, but estimate changes from the mid-1950s to the mid-1970s. Using aerial photographic techniques on 3629 4-square mile units, this study estimated a drop in public and private wetland acreage of 13.8 million acres, from 108.1 to 99.0 million acres in the lower 48 States. The most recent FWS estimates show a 2.6 million acre drop in wetlands in the lower 48 States, from 105.9 million acres in the mid-1970s to 103.3 million acres by the mid-1980s. The mid-1970s estimate was adjusted up from the previous study because of better classification on improved color infrared aerial photography.

USDA's Soil Conservation Service conducted the 1958 Conservation Needs Inventory, which identified 73.5 million acres of rural, nonfederal land needing treatment for excess water. More than 80% of this land was cropland. Some 172.5 million acres were judged to have drainage problems. Similar statistical spatial sampling methods were used in the 1975 Potential Cropland Survey to record 21.4 million acres of high and medium potential cropland suffering from wetness, but only 181,300 acres were identified as wetland types 3–20 in the Circular 39 classification. The 1977 NRI identified 41.5 million acres of wetland types 3–20. The 1982 NRI inventoried all rural, nonfederal wetlands according to both the older Circular 39 and later Cowardin classifications. It found 78.4 million acres of wetlands. The 1987 NRI reclassified some of the sample points originally visited in 1982 to increase 1982 rural nonfederal wetlands to 83.2 million acres. A loss of 1.2 million acres was estimated to occur between 1982 and 1987, resulting in only 82 million wetland acres by the latter date.

Average annual rates of wetland conversion have generally been falling since the first reliable scientific wetland inventories were taken in the mid-1950s (Table VI). FWS estimated the net rate of wetland conversion between the mid-1950s and mid-1970s at 455,000 acres per year, mostly from inland (palustrine) wetlands. Eighty-seven percent of the 13.8 million acres of wetlands converted were to agricultural uses and 8% were to urban uses. A more recent study by FWS using similar methods records a decline in average wetland conversion to 288,900 acres per year for the mid-1970s to mid-1980s. Conversions to agricultural use accounted for a smaller 56% of average annual losses. However, much of the 41% converted to other uses was cleared and drained, possibly intended for agricultural use, but had not yet been put to an identifiable use at the end of the period. Urban uses were 3% of losses. Based on changes at NRI sample points between 1982 and 1987, the rate of conversion dropped to 130,800 acres per year. Agriculture accounted for 38% of wetlands converted. A specific inventory of wetland NRI points done in 1991 provided an estimate of 107,750 acres of wetland lost annually between 1987 and 1991, of which agricultural conversion accounted for only 27%.

B. Economics of Conversion for Agriculture

Agricultural conversion has historically been a far more widespread cause of wetland conversion than urban uses. Factors that affect the economics of agricultural wetland conversion are technology, effective crop prices, farm program considerations, tax effects, and land values. Technological change can alter the profitability of wetland conversion by reducing the cost of conversion. An example is the introduction of plastic subsurface drain tile continuously installed using drainage plows. Technological advances such as continuous corrugated plastic tubing, improved manufacturing methods and materials, advances in field installation techniques and machinery,

TABLE VI

Extent and Changes in Wetlands, 1954 to 1991

	National Wetland Status and Trends[a]					National Resources Inventory[b]			
	1954	1954–1974	1974	1974–1983	1983	1982	1982–1987	1987	1987–1991
				Million acres					
Wetlands inventoried	108.1		105.9 (99.0)		103.3 (78.4)	83.2		82.0	
Average Annual				Thousand acres per year					
Net change[c]		455.0		288.9			124.0		na
Conversion to									
Agriculture		600.0		237.5			50.0		29.3
Urban/development		55.0		14.1			56.0		58.3
Other		35.0		171.7			24.8		20.3
Total		690.0		423.2			130.8		107.8
				Percentage of total conversion					
Conversion to									
Agriculture		87		56			38		27
Urban/development		8		3			43		54
Other		5		41			19		19
Total		100		100			100		100

Sources: [a] U.S. Fish and Wildlife Service, National Wetland Status and Trends Analysis, mid-1950s to mid-1970s and mid-1970s to mid-1980s. Excludes Alaska and Hawaii. The 1974 wetland extent was increased because of better photo interpretation using color infrared photography not available earlier. [b] Soil Conservation Service, USDA, National Resources Inventories, 1982, 1987, and 1991 Wetlands Update. Includes only rural, nonfederal land. Excludes Alaska. Wetland extent not estimated in 1991.

[c] Conversion of wetland to nonwetland uses, plus increases in wetlands due to restoration, abandonment and flooding.

and improvements in design and engineering, such as laser guidance, reduced the real cost of surface drainage from a high of $225 per acre in 1900 to $140 per acre in 1985 (1985 constant dollars). Subsurface drainage costs have declined more dramatically, halving between 1965 and 1985 to a cost of $415 per acre.

The principal way in which the agricultural business cycle affects wetland conversion economics is through the effective price of the commodity being produced. When market prices for commodities increase, as they did during the 1970s and early 1980s, gross revenues and net returns from crop production increase. If these conditions are expected to prevail for a sufficiently long period of time, if increases in crop production along the intensive margin (i.e., greater use of nonland inputs), and if other opportunities to develop new cropland at lower cost are limited or exhausted, producers will favorably consider investments in wetland conversion. Regardless of any wetland protection policies, much of the incentive for new wetland conversion was undercut in the mid-1980s as crop prices fell and other tax and subsidy incentives were eliminated.

In agriculture, no less than other economic sectors, income tax treatment of investments and expenses affects their profitability. Before the 1986 tax reform act, wetland conversion investments were favored in the Internal Revenue Code in a number of ways. First, expenses for land clearing, drainage, and land shaping could be deducted from farm income. Deducting these expenses instead of capitalizing them decreases the taxable basis of the improved land, resulting in larger capital gains when the land is sold. Deductions were also available for depreciation of machinery used in wetland conversion under the accelerated cost recovery system and for interest payments on debt financing conversion investments. An investment tax credit equal to 10% of the depreciable investments associated with conversion was also available. Finally, up to 60% of long-term capital gains realized from the sale of improved farmland could be excluded from ordinary income and taxed at preferential capital gains rates. In addition to farm income, all of these tax reducing provisions were available to shelter nonfarm income and could easily be applied to incomes of passive investors. The effect of these provisions was to reduce the cost of wetland conversion, providing an artificial incentive for further conversion activity.

Prior to 1985, U.S. farm price and income support programs were another important factor in wetland conversion economics in two ways. Before market prices for crops rose in the mid-1970s and after they fell in the mid-1980s, loan rates and target prices in the farm programs set effective prices for commodities higher than prevailing market prices. Basic eligibility for price and income support programs is determined by crop acreage bases and voluntary compliance with farm program set aside provisions designed to control supplies of crops produced. The producer's payment is based on the crop acreage base, less the set aside requirement, times the program yield, times the deficiency payment. Converting wetlands and other kinds of land for crop production in high-price periods insures a higher gross subsidy in low-price years when the programs operate. Further, to the extent that converted wetlands are not completely drained, these may be the least productive croplands that can be idled to meet set aside requirements. Thus, U.S. price and income support programs created an artificial incentive to convert wetlands, as well as other land.

The final economic factor in wetland conversion is land values. The income theory of value says that the value of land or any productive asset equals the capitalized net present value of the expected stream of earnings possible with that asset. In the case of farmland, current values should be no greater than expected net returns from farming. However, there is a degree of speculation in all asset valuation because of differing expectations of future changes in prices, costs, or other factors affecting returns. Because of the rapid increase in farm prices during the 1970s, expectations of continued price increases caused farmland values to exceed values based on current net returns. Such "speculative bubbles" affect investment decisions, including the decision to convert wetlands, and inevitably burst. High expectations concerning eventual values of cropland converted from wetlands in the later 1970s were subsequently shown to be ill conceived as supply responded and commodity prices dropped. Many wetlands converted to agriculture during this period have since been abandoned.

C. Profitability of Conversion

The economics of wetland conversion are identical to any other economic investment. The rational decision to undertake drainage, dredging, filling, or other physical means of conversion depends on the expected stream of future revenues, including any increase in revenues that can be earned on the converted wetland, minus the cost of conversion and the expected stream of future production costs, all discounted to present value terms. If the expected revenues exceed the expected costs, and the percentage return on assets invested in the conversion exceeds that of alternative investment opportunities, the rational person would convert the wetland.

There are a number of ways in which converting a wetland can be profitable for a landowner. Some wetlands are attractive sites relative to alternative sites and produce higher revenues because the wetland confers some particularly desirable feature on the land. Examples include access to recreational waters in the case of marina development and the great natural fertility of bottomland soils that are continuously enriched by fresh deposits of silt.

Other wetlands are a nuisance that increases the cost of production unless converted. An example is prairie pothole wetlands within farm fields that require more turns for machinery and form point rows and dead rows that cannot be planted or harvested. Wetlands within fields can also restrict machinery choices to smaller, lighter, less economical sizes. Another example is isolated wetlands in housing developments that reduce the number of buildable lots, increasing the cost of each remaining lot.

Still other wetlands are converted incidental to economic activity. Flood control measures may not be intended to convert wetlands at all, but can restrict the cyclical inundation that naturally occurs in bottomland hardwood wetlands. Construction of dugouts as catchments for irrigation water, a common practice for center pivot irrigation in Nebraska, can lower water tables and incidentally destroy adjacent wetlands.

Finally, some wetlands are converted for the investment or speculative gain to be had. This accrues from the difference between raw land costs for unconverted wetlands and developed values for buildable or farmable land, including conversion costs. This difference can often provide enough motive for much wetland conversion.

Changes in economic conditions alone between the mid-1970s and late 1980s have made much, if not all, agricultural drainage unprofitable. Reduced prices for agricultural commodities and increased prices for crop inputs have squeezed profits, generally making investments in wetland conversion less desirable. The effects of the swampbuster and income tax reform provisions over the past decade generally reduced wetland conversion profitability. These reforms, combined with reduced profitability due to market conditions, made almost all agricultural wetland conversion unprofitable in the late 1980s and early 1990s. As long as agricultural commodity prices remain low and dependence on farm program participation to supplement farm incomes remains, there will be little economic incentive for agricultural wetland conversion. There may still be incentives for enhanced drainage on farmed wetlands and the motivation for eliminating "nuisance" wetlands remains, as long as swampbuster sanctions can be avoided. [*See* PRICES.]

V. Policy Development

A. What is "No Net Loss?"

The goal of "no net loss" of wetlands came to prominence in then-Vice-President Bush's election campaign as part of his promise to be the "environmental President." President Bush never backed away from that goal, and President Clinton's wetland plan promises to embrace "no net loss" through a new Executive Order. The origin of the "no net loss" goal goes back to FWS's mission to protect waterfowl, and to certain private initiatives, such as Ducks Unlimited work to conserve and restore waterfowl habitat. As early as 1954, FWS associated waterfowl conservation with wetland habitat. The National Wetland Priority Conservation Plan, required under the Emergency Wetland Resources Act of 1986, emphasizes conserving and restoring wetlands. The North American Waterfowl Management Plan, a joint agreement and treaty between the United States and Canada, also calls for restoring former waterfowl habitat. The North American Wetlands Conservation Act establishes a Wetland Trust Fund, authorizes appropriations of $15 million annually over 1991–1994, and establishes the North American Wetlands Conservation Council to approve wetland restoration projects. Another step on the road to "no net loss" occurred in North Dakota. The Garrison Diversion project was the subject of a compromise between the State of North Dakota, the COE, and environmental groups that had been delaying the project. These parties agreed to a reduced project if North Dakota, among other conditions, adopted a "no net loss" of wetlands program.

The direct antecedent of "no net loss" at the Federal level was the National Wetland Policy Forum. Quoting from their report:

> Although calling for a stable and eventually increasing inventory of wetlands, the goal does not imply that individual wetlands will in every instance be untouchable or that the no-net-loss standard should be applied on an individual permit basis—only that the nation's overall wetlands base reach equilibrium between losses and gains

in the short run and increase in the long term. The public must share with the private sector the cost of restoring and creating wetlands to achieve this goal.

The "no net loss" goal means restricting landowners' property rights to protect a continued stream of public goods from the resources. A fundamental issue raised by a no net loss policy is the appropriate balance between the regulatory and compensatory measures. The public believes fundamental property rights are important and also values the public goods produced by natural resources in private ownership. Society needs to balance these conflicting values and choose between or combine regulation and compensation to achieve that balance.

There is also an issue of conservation versus restoration. Should society put relatively more effort into conserving existing wetland resources than restoring wetlands that have previously been converted? On a pure efficiency basis, conservation avoids adding the cost of restoration on top of the original costs of converting the wetland. The National Wetland Policy Forum and President Bush stated that conservation will not be enough. Unavoidable wetlands losses will occur for overriding public purposes. How do we make up for those unavoidable losses? The only way is some form of a wetland restoration or creation program. In the United States, wetland conservation and restoration have been accomplished voluntarily, in response to a growing array of positive incentives provided by conservation programs, and under requirements of regulatory and quasi-regulatory programs. Policies affecting agricultural wetlands have been evolving for more than 200 years.

B. Evolution of Agricultural Wetland Policy

For the first 200 years of U.S. history, the Federal Government approved of and assisted with wetland drainage to further public health and economic development goals. Between 1849 and 1860, the Swampland Acts granted 64.9 million acres of wetlands to 15 States. Grants were made on the condition that proceeds of wetlands sold to individuals be used for reclamation projects. For the first 70 years of this century, USDA had a policy of direct financial and technical assistance to the farm community for wetland drainage. Flood control, navigation, stream channelization, and highway projects also contributed to agricultural drainage by providing drainage outlets. While Federal aid was not solely responsible for wetland drainage, it did provide positive economic incentives.

Most direct incentives ended in the 1970s for a variety of reasons, culminating in Executive Order 11990 issued in 1977. This ordered agencies of the Federal Government to ". . . minimize the destruction, loss or degradation of wetlands . . ." and to ". . . avoid direct and indirect support of new construction in wetlands wherever there is a practicable alternative . . ." Indirect Federal assistance for wetland conversion in agriculture was eliminated by the so-called "swampbuster" provision of the 1985 FSA and changes in the 1986 Tax Reform Act. The swampbuster provision was a quasi-regulatory policy that made a farm operator ineligible for price support payments, farm storage facility loans, crop insurance, disaster payments, and insured or guaranteed loans for any year in which an annual crop was planted on converted wetlands. Tax reform restricted or eliminated many provisions that indirectly subsidized agricultural wetland conversion. Among these were deductions for land clearing expenses, deductions for soil and water conservation expenses, and preferential treatment of capital gains, including capital gains realized from draining wetlands.

Further changes to agricultural wetland policy were also included in the 1990 Food, Agriculture, Conservation, and Trade Act (FACTA). One important change closed a loophole in the swampbuster provision. After 1985, producers who converted a wetland and planted an agricultural commodity lost farm program benefits on their entire operation. However, eligibility for benefits was retained for any year in which no crop requiring annual tillage was planted despite wetland destruction. The 1990 FACTA expands the swampbuster "trigger" to include conversion of a wetland to make production possible. Converting a wetland to make production possible invokes loss of benefits and benefits cannot be restored until the converted wetland is restored.

In return for this change, commodity interests obtained some concessions on swampbuster. The minimal effect clause, which exempts conversions that are determined to have minimal effect on the hydrological and biological properties of the wetland, was expanded to allow mitigation. Mitigation is the term for wetland restoration or creation at another site to replace wetlands lost to development. In the changes to swampbuster, a farmer can drain a wetland without losing farm program benefits if another prior converted wetland somewhere else on the farm or in the local area is restored.

Farm groups also convinced Congress to change the so-called "drop dead" penalty in the swampbuster provision. The previous penalty meant loss of all farm program benefits, even for small wetland conversions. The new graduated penalty provision allows an operator to violate swampbuster once in 10 years if the wetland is restored and if the conversion occurred in good faith. The penalty ranges from $750 to $10,000, depending on the severity of wetland destruction. While substantial, these fines are less than farm program benefits which may run to several hundred thousand dollars. The operator remains ineligible for farm program benefits until the converted wetland is either restored or mitigated.

Agricultural wetland policy has turned from subsidizing conversion of wetlands for agricultural use to elimination of direct and indirect subsidies for conversion. The next step in the evolution of policy is toward positive incentives for wetland protection and restoration, some of which were passed in the 1990 FACTA.

C. Federal Wetland Regulation

Historically, Congress created financial incentives in agricultural programs to compensate farmers for changes in the bundle of property rights that they can exercise on their land. Some view the swampbuster provision as regulatory. In fact, it is a condition on receipt of benefits in a voluntary program, albeit one that many farmers view as necessary to their economic survival. Many States have wetland regulations that limit what can be done to drain or alter these lands. The only Federal program regulating wetland conversion was and remains Section 404 dredge and fill permit requirements enacted in the 1972 Federal Pollution Control Act amendments. Section 404 evolved to deal primarily with marine and estuarine wetlands associated with navigable waters. The COE administers Section 404 with oversight by EPA. Section 404 permits are justified under the legal authority to limit discharge of dredge and fill material into navigable waters. This justification is derived from a long-recognized Federal jurisdiction over navigation. However, Section 404's bark is worse than its bite. In 1990, of more than 15,000 individual permits, 67% were approved, 30% were withdrawn by applicants or processed as general permits, and only 3%, or 500 permits, were denied. An estimated 75,000 activities were also allowed under one of 37 COE regional or nationwide general permits, including most agricultural activities.

In the past, drainage was excluded from Section 404 requirements. Thus, the program has not affected agriculture to any extent because most on-farm conversion involves drainage rather than dredge and fill. In addition, "Normal agricultural and silvicultural practices . . . ," such as maintenance of drainage ditches and levees, have been exempt from Section 404 permit requirements. Section 404 regulations exempt most routine agricultural practices. Between 1972 and 1987, these exemptions and a general reluctance by the COE to treat land cleared for agricultural production as wetlands meant that Section 404 had little impact on agriculture except where extensive new conversion was occurring.

However, after the "no net loss" goal and the 1989 manual, opposition to more aggressive field implementation of Federal wetlands policies by farmers, developers, and small landholders was being expressed to Congress and at higher levels in the Bush Administration. An EPA/COE regulatory guidance letter and more recent regulations issued in 1993 further exempted farmland converted prior to 1985, consistent with the scope of USDA's swampbuster program. Nevertheless, changes in levees, dikes, and drainage on a larger amount of farmland still classified as wetlands and previously ignored now come under Section 404's purview. Most normal agricultural activities are allowed to continue under 404 scrutiny, but conversion of wetlands to agricultural use and conversion of wetlands used for agricultural production to more developed uses requires a Section 404 permit.

None of these efforts to moderate the new policies occurred soon enough or went far enough to head off rapidly coalescing opposition. Bolstered by successful cases in the Claims Court of the United States and the prospect of a conservative majority in the Supreme Court, property rights interests targeted wetland regulation as an opening wedge in rolling back all kinds of regulation designed to promote the general welfare, unless compensation is provided to landowners. Wetland regulation was attacked as a "taking" without compensation, proscribed under the Fifth Amendment to the Constitution.

Representatives Hayes and Ridge introduced regulatory reform legislation which addressed wetland delineation, differential regulatory responses for different categories of wetlands, and compensation for wetlands most severely regulated. Environmentalists responded with the Edwards Bill (Table VII). After protracted internal bickering, the Bush Administration responded with a plan for accelerated regulatory reform issued on August 9, 1991, followed shortly by the proposed 1991 interagency wetland delineation manual, a substantial revision of the 1989 manual.

Little progress was made in implementing the Bush plan prior to the 1992 Presidential election.

The Clinton Administration moved quickly, designating an interagency task force led by the new White House Office on Environmental Policy to craft their own wetland regulatory reform package. On August 24, 1993, the Administration released a plan that proposed the following. First, the Clinton Administration promised to embrace the 1988 National Wetland Policy Forum's goal of no net loss of wetlands by issuing an Executive Order. Second, the fairness, flexibility, and speed of the Section 404 permit process would be increased by establishing a 90-day deadline for most permit issuances, issuing guidance to subject less valuable wetlands with less vigorous permit review for small projects and limited impacts, and establishing an administrative appeals process for COE permit decisions. Third, differences over wetland delineation were resolved by confirming use of the 1987 delineation manual pending completion and review of the NAS study, giving USDA's Soil Conservation Service lead responsibility for identifying wetlands on agricultural land, and exempting 53 million acres of prior converted cropland from both swampbuster and Section 404 requirements. Additional wetland protection was promised by closing a loophole that allowed wetland destruction through drainage and excavation that did not involve dredge and fill. Incentives were promised for State, tribal, and local governments to engage in watershed planning to avoid conflicts between wetland protection and development. Finally, the Administration promised to support wetland restoration by increasing funding for USDA Wetland Reserve Program (WRP), supporting voluntary, nonregulatory restoration programs, and endorsing use of mitigation banks.

The Clinton wetland plan consists of a mix of immediate and long-term administrative actions and legislative proposals. The COE and EPA issued final regulations exempting prior converted cropland and extending the scope of regulated activities to include drainage and excavation, required as part of the settlement of a successful lawsuit by the National Wildlife Federation. They also issued regulatory guidance on flexibility in permit review and joined with USDA and Interior on a statement of principles regarding wetland delineation on agricultural lands. A new Executive Order embracing the no net loss goal, administrative appeals, permit deadlines, and mitigation banking will require further work. Much of the Administration's plan is encompassed in Senate Bill 1304, introduced by Senators Baucus and Chafee as part of work on reauthorization of the Clean Water Act and incorporated into Senate Bill 1114.

Agencies dealing with wetlands are more optimistic that problems surrounding Federal wetland protection have been successfully addressed by the Clinton Administration's plan than at any time in the recent past. After stymieing progress on Clean Water Act reauthorization in the 102nd Congress, compromises also seem within reach in the 103rd Congress.

D. Positive Conservation Programs

While regulatory and quasi-regulatory agricultural wetland protection policies were evolving, there were programs designed to give positive incentives to conserve wetlands on private lands. USDA's Water Bank program was authorized in 1970 and amended a decade later. In return for annual per-acre payments, landowners agree not to burn, drain, fill or otherwise destroy the character of enrolled wetland areas for 10 years. Additional cost-sharing payments are available for installation of conservation practices designed to maintain vegetative cover, control erosion, improve habitat, conserve surface water, or manage bottomland hardwoods.

Agreements have been effected in 15 states, but the program has concentrated in the Prairie Pothole region. Some 4,400 agreements have been contracted covering almost 500,000 acres of land at an average rental cost of $15 per acre. Only one-third of the land under Water Bank agreements is wetland, while the remaining two-thirds is adjacent upland area on which agricultural use is restricted to protect wetland values, such as waterfowl nesting.

In 1989, Conservation Reserve Program (CRP) eligibility was expanded to include wetland that had been cropped for at least 2 years between 1981 and 1985, but had not been drained. About 410,000 acres were enrolled in 1989, most in the Prairie Pothole region of North Dakota, South Dakota, and Minnesota.

Under the Small Wetland Acquisition program, FWS can either purchase a wetland and the surrounding upland acreage outright, or enter into a permanent easement agreement restricting wetland use. Compensation is made on a one-time basis with the payment varying according to land values in the immediate area and the development potential of the wetlands. Permanent easements on about 126,000 acres of wetlands and adjacent areas included in National Waterfowl Production Areas and refuges be-

TABLE VII
Comparison of Congressional and Administration Wetland Regulatory Reform Proposals

Item	H.R. 1330 Hayes/Ridge	H.R. 350 Edwards	S. 1304 Baucus/Chafee	Bush August 9, 1991, Plan	Clinton August 24, 1993, Plan
Delineation	Requires all three indicators: surface saturation for 21 days. Delays any revision of manuals until completion of NAS study.	Requires consistency with a NAS study of 1989 and 1991 manuals under EPA.	Wetlands are defined in the act using the COE definition, including isolated wetlands. Continues use of 1987 Manual until completion of NAS study.	Proposed 1991 manual in response to public comments on 1989 manual.	Urges Congress to define waters of the U.S. and wetlands, including isolated wetlands. Continues use of 1987 Manual until completion of NAS study.
Categorization	Three Classes: A. Critical B. Significant C. Limited or marginal.	None	Under wetlands and watershed management planning, provides for assessment of functions and relative value of wetlands within management units and categorization of activities according to adverse effects.	Limited number based on function, value, scarcity; favored nationwide a priori mapping of "high," "medium," and "low" value wetlands with differential regulatory response.	Opposes a priori categorization; Issued 404(b)(1) guideline flexibility guidance, development of wetlands functional assessment tools, encourages advance planning, and regionalized general permits.
Regulatory response	A. Generally denied permits B. Sequencing applies considering six specific factors; permits generally issued within 6 months C. No permit required.	No permit if there is a practical alternative with less environmental impact; fast track minor permits within 60 days; reduce paperwork and delays.	Issued within 90 days unless a NEPA or ESA impact statement is required, a Federal or State Governor requests a delay, or COE and the applicant agree more time is needed; EPA must determine restrictions on discharges within 180 days after a permit is issued; establishes administrative appeals procedure by landowner or third party.	Six-month approval; sequencing for highest category; general permits for low-value; mitigation required.	COE regulations to be revised within 1 year requiring permit decision within 90 days, except where NEPA or ESA impacts; Administrative appeal process required for permit denials, but not by third party.
Regulatory scope	Expands to include drainage, channelization and excavation; exempts normal ag practices, man-made wetlands, activities under approved State plan; prior converted cropland is in Type C.	Expands to prohibit discharge of pollutants or other alteration of navigable waters, including draining, dredging, channelization, flooding, clearing vegetation, obstructions, and other water diversions; exempts normal ag practices, man-made wetlands; requires rule on prior converted cropland	Expands to include draining, mechanized land clearing, ditching, channelization, or other excavation; exempts an expanded list of normal ag practices, man-made wetlands.	Supports legislation to expand to drainage and other activities, exempts man-made wetlands, normal ag practices, prior converted cropland.	Issued final regulations expanding "discharge of dredged materials" to excavation activities, including ditching, channelization, and mechanized land clearing and nontraditional use of pilings; exempts normal ag practices, prior converted cropland, and man-made wetlands.
State program assumption	Specifies conditions for State programs, COE must respond or approve within 1 year; States may develop management plans; COE must approve within 60 days.	None	EPA grants for State conservation plans; allows State general permits, but not unless part of a wetlands and watershed management plan after 1996.	Encourages flexibility for State programs that achieve 404-level protection, including wetlands adjacent to navigable waters	Provides technical and financial assistance for State/Tribal/Local assumption and programmatic general permits; encourages CWA funding for wetland and watershed planning.

General permits	Allows general permits with reporting and mitigation	Clarifies general permit program and requires reporting of effects	Encourages use of State, regional, or nationwide permits when impacts on wetlands are minimal and not cumulative. Expands programmatic general permits for existing State/Tribal/Regional/Local programs if part of a wetlands and watershed management plan; and to USDA's Swampbuster program, limited to 5 years with review.	Encourages use of State general permits	Requires COE guidance on State/Tribal/Regional/Local programmatic general permits; regionalizes existing general permit on isolated and headwater wetlands
Mitigation banking and restoration	COE must establish a bank in each State; includes restoration, enhancement, preservation, or creation.	Establishes restoration pilot project	Requires COE/EPA rules within 1 year, mitigation restricted to advance restoration.	Requires mitigation banking proposal related to categories	Requires COE guidance on concurrent mitigation requirements and COE/EPA guidance on mitigation banking, encourages banking and requests legislation to fund banks using CWA State Revolving Fund monies
Coordination	"Unified" in COE	Interagency agreements	Requires coordination with USDA; Exempts prior converted cropland and nontidal drainage and irrigation ditches; swampbuster programmatic general permit.	Requires guidance for better Federal coordination.	Gives USDA responsibility for delineation and mitigation on ag lands; Continues expedited review and resolution of concerns under 1992 404(q) MOA
Watershed management planning	States may develop management plans; exemptions for activities under approved State plan.	None	Establishes State and substate wetlands and watershed management units, management entities, plan development requirements, and approval process, provides funding, expedited permit review, mitigation banking, and programmatic general permit incentives for planning; grants for State wetland conservation and restoration plans.	Encourages management plans as part of categorization and wetland mitigation banking.	Request CWA amendment to authorize development of integrated wetlands and watershed planning; endorses State/Tribal wetland conservation plans; provides greater integration with 404 permit review
Compensation	Type A wetland owners eligible	Provides for tax deductions for diminution in value for compatible, nondegrading uses of wetlands, directs establishment of Wetlands Stewardship Trust to receive such donations of property easements	None	None	None; encourages 404 operation to avoid "takings."

tween 1981 and 1988 averaged $279 per acre, while purchases averaged $800 per acre.

An agricultural wetland reserve was established as part of the 1990 FACTA. The Act called for restoration of one million acres of cropland to wetlands. The WRP requires permanent or long-term easements with the landowner to restrict agricultural use of restored wetland. Eligibility extends to existing cropped wetlands, restorable wetlands, other noncropped wetlands (such as Water Bank lands), riparian corridors, and critical wildlife habitat. Adjacent cropland that may be used as a buffer zone or is functionally related to the restored wetland is also eligible. Economic uses of the restored wetlands can be included in the restoration plan that will help reduce the cost of acquiring easements, if those uses are not incompatible with the basic objective of preserving the wetland. Costs of such a reserve are to include the easement value, which cannot exceed the market value of the land, and restoration cost sharing for the actual restoration of up to 100% for permanent easements. A total of 55.6 million acres of cropland converted from former wetlands is eligible for WRP, which should make the 1-million acre target easy to achieve.

Initial WRP enrollments in 1992 were restricted to nine pilot states. Owners of more than 462,000 acres expressed interest in WRP and almost 250,000 acres were offered for enrollment by producers, from which USDA selected 49,888 acres at a cost for easements and restoration of $46.4 million. Despite the large response to the pilot WRP program, Congress provided no additional funding toward the 1 million acre goal in FY 1993, prompting fears that the program would not be pursued. However, $67 million was provided for 1994 to enroll an additional 75,000 acres. In addition, money from the $60 million provided for emergency flood relief in the Midwest can be used to enroll land in WRP when the cost of rebuilding levees and ditches is too great. President Clinton's 1995 budget contains $283 million for WRP.

A more comprehensive wetland restoration effort is envisioned in the 1992 report of an NAS panel on restoration of aquatic ecosystems. Considering the scientific and technical feasibility of wetland restoration, the NAS panel recommended an ambitious goal of restoring wetlands at a rate that offsets future losses and results in a net gain of 10 million acres of wetlands by 2010, an amount equal to 10% of losses since 1780. The report contains numerous recommendations to implement this goal, including an interagency, intergovernmental planning process for a national aquatic ecosystem restoration strategy, a unified agency to carry out the plan, enhancement of existing Federal programs to facilitate restoration, and establishment of a National Aquatic Ecosystem Restoration Trust Fund.

A final source of increased wetland restoration is the mitigation banking provision in the 1990 Intermodal Surface Transportation Efficiency Act (ISTEA). While State highway departments previously established mitigation banks to compensate for unavoidable wetland conversion in the path of new highways, this provision is the first to allow Federal highway monies to fund mitigation banks early in the design phase. If carefully implemented, this provision will let wetlands be restored, created, or enhanced long in advance to more than offset projected losses, resulting in net gains of wetland acreage, often on former agricultural land. Specific wetland restoration projects, like the dechannelization of Florida's Kissimmee River, are also included in new authorities of the COE contained in the Water Resources Development Act of 1990.

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Wheat Breeding and Genetics

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Glossary

Cultivar Currently or previously cultivated (commercially grown) variety

F_n F is an abbreviation for filial generation which is any generation after the parent generation and "*n*" is the number of generations after the parent generation (e.g., F_2 is the second generation after the parent generation)

Genome Basic (monoploid) set of chromosomes in a progenitor species; polyploid species have multiple genomes

Genotype Total genetic constitution of an organism

Phenotype Total observable characteristics of an organism

Wheat breeding can be described as human-made evolution of wheat to serve humanity. Wheat breeding is both the science and art of genetically improving wheat by creating genetic variation, inbreeding to create variants, selection of superior variants, and evaluating the selections under natural conditions. Its goal is new cultivars that are superior to existing cultivars for at least one important trait.

I. The Biology and Uses of Wheat

The genetics and breeding of any crop are determined by its biology. Cultivated wheats are predominantly two species, namely, bread or common wheat (*Triticum aestivum* L.) and durum wheat (*T. durum* L.). Common wheat is the more predominant wheat and is classified by its physical characteristics and end uses. Hard common wheats are used to make breads and rolls. Soft common wheats are used to make cookies, cakes, and crackers. Durum wheat is used mainly to make pasta and semolina products. Hard, soft, and durum wheats can be harvested for forage and their straw used for animal feed or bedding. Hence, wheat can be developed for sophisticated baking processes or for total biomass as is required in a productive forage crop. [*See* WHEAT PROCESSING AND UTILIZATION.]

Both cultivated wheat species are allopolyploids. Common wheat is a hexaploid ($2n = 6x = 42$ chromosomes) and has three genomes (designated AABBDD). Durum wheat is a tetraploid ($2n = 4x = 28$ chromosomes) and has two genomes (designated AABB). Diploid ($2n = 2x = 14$ chromosomes) *Triticum* relatives are rarely grown commercially.

Hexaploid and tetraploid wheats evolved by two evolutionary processes. The original progenitor species is not known, but was a diploid. By divergent evolution, it evolved into numerous diploid species including *T. monococcum*, *T. tauschii*, barley (*Hordeum vulgare*), and rye (*Secale cereale*). The second evolutionary process was convergent evolution in which by natural hybridization and spontaneous chromosome doubling, polyploid species were formed. For example, *T. monococcum* (the A genome donor) hybridized with an unknown *Triticum* species (the B genome donor) to form *T. dicoccoides*, the progenitor of durum wheat, genomic constitution AABB. A second hybridization occurred between *T. dicoccoides* and *T. tauschii* (the D genome donor) to form common wheat, genomic constitution AABBDD

The two evolutionary processes have two notable effects. First, divergent evolution greatly increased the genetic diversity within wheat and its relatives. As discussed later, genetic diversity is critical for plant breeding. Also, the effective use of genetic diversity has made wheat the most widely grown cereal in the world and it has the highest total grain production. Second, convergent evolution greatly increased genetic redundancy (having multiple genes code for similar proteins or nucleic acid polymers that are involved in a process) within wheat. As discussed later, genetic redundancy allows chromosomal manipulations and breeding strategies that are not possible in diploid crops. [*See* EVOLUTION OF DOMESTICATED PLANTS.]

Both common and durum wheat are naturally self-pollinating. Two other propagation mechanisms are common in plants, cross-pollination and asexual reproduction. The mechanism of reproduction is important because it largely determines the breeding methods that are used. In self-pollinated crops, it is often difficult to make a cross between two different plants, but it is very easy to allow the plants to inbreed by selfing. Self-pollinated crops are usually marketed as pure-lines (synonymous with inbred line). In cross-pollinated crops (e.g., corn), it is very easy to make a cross, but then can be very laborious to inbreed the progeny. Cross-pollinated crops are usually marketed as hybrids or open pollinated populations or synthetics (the parents are selected and allowed to random mate, the progeny seed is sold as the synthetic). There are many forms of asexual reproduction including fragmentation (e.g., cuttings, tubers) and apomixis, but all are a form of cloning (making an identical copy of the original plant). In cloning, it is difficult to introduce new traits, but it is very easy to maintain the existing plant and its traits.

II. Phases of a Wheat Breeding Program

All breeding programs have five main phases: (1) defining the problem and setting the objective, (2) identifying and incorporating useful genetic variation, (3) inbreeding and selection among the resultant variants, (4) evaluation of selected elite lines, and (5) cultivar release. Every phase is critical to the overall success of the breeding effort. Wheat is grown in widely differing environments with different diseases and insect pests and has a multitude of uses. Hence, identifying the problem and setting the objective is the starting point for all wheat breeding efforts. If done poorly, the breeding effort will inevitably be unsuccessful. With the diversity of wheat growing environments and uses, it should be of little surprise that the germplasm used, breeding methods, and release procedures will also differ greatly. [*See* CULTIVAR DEVELOPMENT; PLANT GENETIC ENHANCEMENT.]

III. Identifying and Incorporating Useful Germplasm

Once the breeding objective is determined, the next step is to find germplasm that has the trait of interest and determine how it is inherited. For our purposes, inheritance can be defined as how closely do the progeny resemble the parents. There are three types of phenotypic traits. Traits that have discrete classes are known as qualitative traits. Examples of qualitative traits include seed color and most disease and pest resistances. Qualitative traits are controlled by relatively few major genes (genes that have distinguishable effects). Traits without distinct classes, but having continuous variation, are known as quantitative traits. Examples of a quantitative trait are grain and forage yield. Quantitative traits are controlled by many genes, have cumulative (but not distinguishable) effects that are often greatly modified by the environment. The final class of traits are those that resemble quantitative traits in that they exhibit continuous variation but in this case the variation is due to the environment and not due to genetics. For these traits there is no useful genetic variation or all of the known genetic variation has already been used to improve wheat. An example of a trait with little useful genetic variation is resistance to wheat streak mosaic virus. An example of a trait where most or all of the genetic variation has already been used to improve wheat is winterhardiness, the ability of winter wheat to survive the winter. After initial gains in winterhardiness, little progress has been made. Fortunately, the last group of traits is rare. Where there is no useful genetic variation or all of the genetic variation has been previously used, wheat breeding will be ineffective. [*See* PLANT GENETIC RESOURCES; PLANT GENETIC RESOURCE CONSERVATION AND UTILIZATION.]

In wheat, the main method of introducing genetic variation is by sexual hybridization (crossing two or more different genotypes). Because wheat is naturally self-pollinated, the female plant is hand emasculated and subsequently fertilized by pollen from the male plant. Most crosses are between pure-lines (S × T, where S and T are pure-lines, the cross is known as a single cross) or between the F_1s of pure-lines [(S × T) × U, where U is also a pure-line, the cross is known as a three-way cross; or (S × T) × (U × V) where V is also a pure-line, the cross is known as a four-way or double cross]. When pure-lines are crossed, all the gametes from S will be identical to each other, as will the gametes from T. Hence, each F_1 seed of the single cross should be genetically identical. If the pure-lines are not completely pure (how this can occur will be discussed later), care must be taken to cross a number of random plants within S to a number of lines within T to accurately represent S and T. The situation becomes considerably more complex in three-way and double crosses. Using the three-way cross as an example, the gametes from (S × T) will segregate for the traits that S and T differ. The gametes from U should all be identical. Hence, to accurately represent the three-way cross, (S × T) × U, enough three-way cross F_1 seed should be made to represent the variation between S and T. Obviously, even more F_1 seed is required in double crosses where the seed must represent the variation between S and T, and between U and V, and with the cross combination. For this reason, most wheat breeders use single or three-way crosses.

With the relatively recent discoveries of genetic male sterility and of chemicals that cause male sterility by damaging the pollen in wheat anthers, it is possible to develop in wheat populations similar to those in cross-pollinated crops. However, neither genetically or chemically induced male sterility is widely used and it remains to be seen if population improvement will be successful in wheat.

If sexual hybridization is the predominant method of increasing genetic variation within breeding populations, the critical question is how to select parents having the desired traits. There are three important gene pools available to wheat breeders. The most important and commonly used gene pool includes lines from the breeding program or from other breeding programs in areas of similar climate, diseases, insects, and with similar end use. This gene pool will include wheat lines from neighboring areas, but will also include lines from similar climatic regions that may be separated by large distances. For example, the wheats of Turkey and the countries to its north have provided the genetic foundation for wheat in the U. S. Great Plains. Even today, wheats are exchanged and readily used in breeding programs in both regions. The reason for concentrating on this gene pool is that plant breeding requires the accumulation of many genes for adaptation, disease and pest resistance, and end use quality. By crossing lines that have similar traits or characteristics, the likelihood is increased that many of the important genes are already identical or similar between the two lines; hence, there will be less segregation among the progeny. While it may sound contradictory to make a cross to increase the genetic variation within a breeding population and then use as parents lines that may have many genes in common, the difficult task facing wheat breeders is to improve wheat for some traits without reducing the value of the other traits. This goal requires building upon the already accumulated base of beneficial genes. Also if there is too much variation within the breeding population, it becomes very difficult to identify superior lines among average lines. Except for very specific traits, wheat breeders have always made more progress by crossing good lines to good lines than by crossing good lines to poor lines. In the latter crosses the genetic variation may be greater, but the population mean is lower so that the resulting selected lines are generally poorer.

The second major gene pool is those lines that are adapted to other regions, have disease or insect resistances that may not be necessary to meet the breeding objective, or have different end use quality. These lines are highly improved lines, but would be considered as being partially adapted or unadapted to the targeted area for the breeding objective. However, these lines will probably still have some genes in common with the adapted germplasm; hence, while introducing more genetic variation than if only lines from the first gene pool were used, the total variation often will still be manageable. The population mean will be reduced, but the increased variation may allow the selection of superior lines. To effectively use this gene pool, three-way or multiple crosses are almost exclusively used. The line from the secondary gene pool will be crossed to an adapted parent and then crossed to the same adapted parent or to another adapted parent. In this way, the three-way cross will have three-fourths of its genes from the adapted wheats and only one-fourth from an unadapted or poor quality parent. Additional crosses to adapted wheats may be needed to increase the proportion of adapted genes in the progeny of the cross.

The final gene pool includes the progenitor species of wheat and their relatives. Because common and durum wheat are polyploids and many of the progenitor species and their relatives are diploids or polyploids that include genomes not found in cultivated wheat, few applied plant breeders work directly with this gene pool. However, wheat cytogeneticists, scientists highly skilled in chromosome and genome analysis, have made tremendous contributions to wheat improvement by transferring genes from the wild relatives and incorporating them into cultivated wheat. Usually the transferred genes control qualitative traits because of the difficulties involved in identifying and maintaining the genetic expression of the trait in crosses. Fortunately, because wheat is a polyploid, it is able to temporarily tolerate under the appropriate conditions, aneuploidy (chromosome loss or gain) and genome loss or gain. Once the gene has been incorporated into wheat (usually through repetitive crosses of the wheat relative and its cross progeny to adapted wheat parents), breeders can manipulate the trait as they would any other trait in wheat.

Occasionally, increasing genetic variation by inducing mutations has been attempted, though with only moderate success. Mutation breeding is more difficult in wheat than in other crops because wheat is a polyploid; hence, there are multiple copies of many important genes. Also some traits are controlled by gene families consisting of multiple genes closely linked together. A mutation in one of the genes will not affect the linked genes or genes at other loci, and hence may not affect the plant phenotype. [*See* PLANT GENE MAPPING; TRANSPOSABLE ELEMENTS IN PLANTS.]

IV. Inbreeding and Selection

Once the objective has been determined and the cross made, wheat breeders must choose which inbreeding and selection system (often referred to as **breeding method**) they will use. Inbreeding is important because it leads to homozygous (pure) lines from a heterozygous cross. Selection is important because only a very few of the homozygous lines will be superior and must be selected. The great majority of lines will be inferior and will need to be discarded.

There are two types of selection: natural selection and artificial selection. Natural selection is done by "nature" and plants that are not adapted to the growing environment perform poorly and may be lost from the population. Every wheat breeder chooses the selection nursery site to have an environment that will increase the beneficial and minimize the negative aspects of natural selection. For example in winter wheat breeding, it is common that the selection nursery be in an environment that will cause winter-tender lines to die. Artificial selection is selection done by the wheat breeder. An example of artificial selection is the breeder selecting for plant maturity. Again the wheat breeder will choose a selection nursery site that increases his or her ability to select. However, artificial selection is more time and labor consuming than natural selection; hence, wheat breeders try to use natural selection to rid their populations of poor plant types (culling selection) and artificial selection to choose the better plant types (positive selection).

The common breeding methods for wheat are: (1) mass selection, (2) pure-line breeding, (3) pedigree breeding, (4) bulk breeding, (5) single seed descent or doubled haploid breeding (the two methods have similar objectives and will be discussed together), and (6) backcross breeding. Each inbreeding and selection method is described in great detail in the references given in the bibliography at the end of this article. In general, the breeding methods differ in how the population inbreeds and how selection is done. In this brief description of wheat breeding, the general outline of each breeding method will be given. The differences between the methods will be discussed to illustrate why one breeding method is chosen over another one. However, it must be recognized that in the hands of a skilled wheat breeder, every breeding method can successfully lead to new wheat cultivars. Finally, it is rare that any breeding method is used in its pure form. In practice, the advantages of different breeding methods often are combined.

The mass selection method was commonly used when wheat was first introduced into a new area. The procedure involves growing a population of wheat and selecting a large number of plants that are phenotypically similar (conversely, discarding a small number of plants that are phenotypically dissimilar from the majority of plants). The mass selected population is very similar to the original population with the exception of the plants that were removed and usually requires less field testing to verify its performance which should be very similar to that of the original population. One of the best examples of mass selection was the introduction of Turkey wheat from Turkey and Crimea to the Great Plains. Off-type plants were discarded and the Great Plains Turkey wheat was formed. As wheat is grown widely in the world, the importance of introduced cultivars that are improved by mass selection has lessened.

Mass selection currently is used when a popular cultivar is grown in an area on the edge of its adaptation zone. For example, Siouxland, a popular winter wheat cultivar developed in Nebraska, was grown in Texas. However, in Texas, Siouxland was discovered to have two plant types: one requiring a short vernalization period and one requiring a longer vernalization period. In Nebraska, the winters are sufficiently long that both types would vernalize. However, in the milder winters of Texas, occasionally only the plant type requiring a shorter vernalization period would vernalize. The Texas wheat breeders selected, using mass selection, the plant types needing a short vernalization period and released Siouxland 89 which was better adapted to Texas growing conditions than the original Siouxland. Probably the greatest use of mass selection is to remove variants (off-type plants) from a released cultivar, thus maintaining its purity.

A second breeding method is the pure-line breeding method. In this method, a number of individual plants were selected from an introduced cultivar. The progeny of the individual plants are grown in rows and the best rows selected. Finally the best rows would be grown in replicated yield trials to determine which selection is best. As opposed to mass selection which maintains many of the attributes of the original population, a pure-line derived from an introduced cultivar is derived from a single plant, and hence can be different from the cultivar. Pure-lines require field testing to verify their performance. As mentioned previously, the importance of introduced cultivars has lessened and with it the importance of the pure-line breeding method. It is currently used as an alternative to mass selection for improving an existing cultivar. As will be discussed later, many modern cultivars are heterogeneous (variable) for some traits. To improve the uniformity of the cultivar, plant breeders can use either mass selection or pure-line breeding methods depending upon whether they wish to keep some of or remove the heterogeneity.

Both mass selection and pure-line breeding involve selection within existing populations, usually cultivars. However, populations must be created for new breeding progress to occur. Four breeding methods (pedigree, bulk, single seed descent and doubled haploidy, and backcrossing) begin with the progeny of a cross (the new population). The four methods differ predominantly on the type of selection and when it occurs, though backcrossing involves a different crossing procedure.

In the pedigree method, the wheat breeder selects plants in the F_2 populations and the progeny (the next generation) of that plant are grown in a progeny row (the progeny row is also known as a "family"). In the next generation, plants again are selected from the better progeny rows and their seed is planted the following season as progeny rows. This process (select plants, plant seed as progeny rows, and select best plants in best rows) of artificial and natural selection continues until there is little segregation within the progeny row and selection must be made solely among rows. The amount of segregation within a row depends upon how many generations of inbreeding have occurred and how successful the breeder has been in selecting for phenotypic uniformity. Usually five to six generations of selfing and selection are needed to obtain uniform lines. In every selected line there will be some heterozygosity which with further inbreeding will become heterogeneity within the line. The earlier selection ends, the greater the heterozygosity and eventual heterogeneity. Because selection occurs every season and careful records must be taken on the selected progeny rows and the plants, the pedigree method is resource and labor intensive. The main advantage of the method is the information obtained by consecutive selection and notetaking. The progeny row will indicate the genetic basis of the traits that are being selected.

Also in nature, it is rare that all of the traits that a breeder wishes to observe occur in the same season. For example, many diseases require high humidity or rain for infection. However, selection for drought tolerance requires low humidity and low rainfall. Hence, it would be very difficult to select for disease resistance and drought tolerance concurrently using the same breeding site. Of course the wheat breeder could separate the seed and plant the progeny in disease- and drought-prone environments, but this would double the size of the breeding nurseries and be even more labor and resource intensive. If one main breeding nursery is used for selection, it is possible that during the course of a cultivar selection at that site, that some seasons may be suitable for high disease infection allowing selection for resistance while other seasons may be suitable for selecting for drought tolerance. Cumulatively the wheat breeder can determine a cultivar's disease resistance and drought tolerance. The pedigree method is still very common today for wheat breeding, though it was probably more popular when wheat breeding was less mechanized and more labor intensive.

In the bulk breeding method, the wheat breeder plants the progeny of a cross in bulk at the selection nursery. The bulk is harvested and a portion of the bulk seed is planted the following year. This process (planting and harvesting as a bulk) is repeated until the population is considered to contain a mixture of predominantly homozygous lines. While the plants are growing in a bulk, natural selection and plant to plant competition occur which are normally beneficial. When semi-dwarf wheats (the green revolution wheats) were first developed there was a concern with the bulk breeding methods that the tall wheat progeny of a tall wheat × semi-dwarf wheat cross would be more competitive and shade the semi-dwarf progeny. While this may occur, the relatively few generations of planting and harvesting as a bulk did not eliminate semi-dwarf plants from the population. Hence, wheat breeders were able to select semi-dwarf wheats from the population even if they were at a lower percentage than might have been expected if no selection or competition occurred. As in the pedigree breeding method, the number of generations of selfing it requires to obtain a mixture of predominantly homozygous plants depends on the number of genes segregating in the cross and the desired level of phenotypic uniformity. Usually five to six generations of selfing are considered ample. The key to the bulk breeding method is that wheat plants are self-pollinated so even plants that grow near each other generally do not outcross (less than 6% and usually less than 1%). When the population consists of predominantly homozygous plants, the wheat breeder selects the plants and sows their progeny as progeny rows. Selection is usually done among rows as the parent plants were predominantly homozygous so there should be little variation within the row. If variation within the progeny row is found, the breeder can discard the row or select plants within the row and plant new progeny rows which should be more uniform. The main differences between the bulk and pedigree breeding methods are (1) the bulk relies almost exclusively on natural selection in the early generations of selfing, and (2) the bulk requires very little record keeping (simply the parents of the cross and the generation of selfing). With the ease of plot planting and mechanical harvest, the bulk method is very popular, particularly in winter wheat breeding where there is usually only one generation per year.

Single seed descent and doubled haploidy are very similar to each other, but very different from the other breeding methods. Single seed descent and doubled haploidy both attempt to rapidly inbreed without natural or artificial selection. Single seed descent breeding is done by starting with a large number of F_2 plants and harvesting a single seed from each plant. The seed is planted and at maturity again a single seed is harvested from the plant. This process (harvesting and planting single seed from each plant) continues until plants that are predominantly homozygous are developed (usually five to six generations of selfing). In this procedure, no selection is normally done, though the original F_2 plants may be selected for important qualitative traits before beginning the process.

In doubled haploid breeding, the gamete from a heterozygous plant is manipulated to form a haploid plant. In wheat, the most common method is anther culture. In anther culture, the anthers of a wheat plant are cultured on media that allow the immature pollen grain (known as a microspore) to form a haploid plant. The chromosomes of the haploid plant are doubled spontaneously or through the use of chemicals such as colchicine which inhibit spindle formation. The doubled haploid plant is completely homozygous and a pure-line. In both single seed descent and doubled haploid breeding the seed from the predominantly or totally homozygous plants are harvested and grown in progeny rows. The selection will be among rows as there will be very little within-row variation.

The advantage of both single seed descent and doubled haploid breeding is the speed with which homozygous lines are developed. Because there is little or no selection, plants can be grown in unrepresentative conditions such as greenhouses or growth chambers. By using these growing environments, single seed descent can produce predominantly homozygous spring wheat lines within 2 years (six generations; approximately 4 months per generation). Winter wheats are more difficult to use in single seed descent because they require vernalization which adds an additional 6 weeks per generation. Doubled haploids can produce homozygous lines within a year. As the doubled haploid process is completed in one generation, it is less sensitive to vernalization requirements and more attractive to winter wheat breeders. Though selection is critical to successful wheat breeding, the ability to produce lines in the absence of selection can also be beneficial. Large international wheat breeding efforts, such as those at the international centers, have the responsibility of breeding for diverse ecogeographic areas. The main breeding center may not represent the targeted areas elsewhere in the world; hence, it would be better to develop lines without selection than to develop lines that were selected in a nontargeted area.

The final breeding method is known as backcross breeding method and in many ways is one type of a crossing procedure. Backcross breeding is used when an adapted wheat cultivar needs to be improved in one or a few traits. After a germplasm line is identified that has the desired trait or traits, the germplasm line (known as the donor parent) is crossed to the adapted parent (known as the recurrent parent). The F_1 seed is planted and the plants are crossed again to the recurrent parent to produce backcross seed. The crossing process continues where the cross progeny are crossed to the recurrent parent. The cross progeny are screened for the trait or traits and only those having the trait or traits are used in the following crosses. This procedure maintains the trait(s) of interest while gradually removing the other traits of the donor parent. The end result of the backcross breeding method is an improved cultivar that is very similar to the recurrent parent but with the extra desired trait or traits from the donor parent. Backcrossing is one of the most predictable breeding methods. This is both an advantage and a disadvantage. The advantage is the predictability which is unusual in plant breeding. The disadvantage is the conservative nature of the procedure in that it often requires five to six cross generations, screening at most backcross generations, and at the end of the process the desired trait may be linked to a deleterious trait or the recurrent parent may no longer be an important cultivar due to more recent releases. One of the reasons why there is little improvement for wheat streak mosaic virus resistance is that the genes incorporated from wild wheat relatives are linked to deleterious genes that reduce the yield or quality of the crop more than the disease. Backcrossing is used extensively when the donor parent is from the unadapted or wild relative gene pool. It is also extensively used when a breakthrough in yield is made and additional traits must be added to incrementally improve the wheat cultivar.

Wheat breeders chose their breeding method by their breeding objective. For example if only one or a few traits need improvement, backcrossing can be used. If a number of traits need to be improved and labor is inexpensive, then the pedigree method may be chosen. If a number of traits need to be improved, labor is expensive, but mechanical planters and harvesters are available, the bulk method may be chosen. When working with crosses involving very high yielding lines where early generation selection may be ineffective, then it may be better to rapidly inbreed using single seed descent or doubled haploidy and then select among the pure lines.

As mentioned previously, it is rare that a single breeding method is used exclusively in the development of a wheat cultivar. For example, a spring wheat breeder may make a cross and then use the pedigree breeding method for two or three generations to select for easily measured traits (for example maturity, disease or insect resistance, plant height). More difficult to measure traits are more challenging to select for in early generations. Hence, a spring wheat breeder may advance the selected lines by single seed descent for two generations during the off season (the season when the crop is normally not grown in the field in his or her target area) and then evaluate the homozygous lines for these traits (yield, end use quality) in the following breeding season. By using both the pedigree and single seed descent method, the wheat breeder was able to select the major genes early in the program, rapidly move through the generations where selection would be less effective, and then thoroughly evaluate the homozygous lines. In winter wheat, the breeder might grow his F_2 and F_3 generations in bulk at a location that usually has a harsh winter, thus letting nature kill the winter tender types. It is best to use natural selection for winter survival because it is very difficult to simulate a harsh winter in a controlled environment. Also, every winter is different; hence, multiple selection environments are preferred. Winterhardiness is controlled by recessive genes; hence, selection can quickly and effectively remove the winter-tender types. The breeder may then use pedigree selection for one or two additional generations to select for major genes.

In this brief discussion of inbreeding and selection methods, the traits being selected have not been discussed in detail. There is a pattern or hierarchy to selection. In early generations, wheat breeders select for traits that are highly heritable and distinguishable. The traits would include disease and insect resistances, plant height and morphology, plant maturity, and plant growth habit (spring or winter for winter wheat, winter survival). Due to the number of lines in a typical wheat breeding program, most of the early generation selections are done visually in environments that have high incidences, naturally or with artificial inoculation, of diseases or insects, etc., that allow the breeder to select the plants having the traits of interest. In the early generations, a wheat breeder may have 2,000,000 or more plants and can select among 40,000 to 100,000 progeny rows.

As inbreeding increases and the lines become more homozygous, the breeder is able to better see what the finished cultivar could be. At this time, the wheat breeder has many fewer lines and begins to select for quantitative traits or traits that are difficult or expensive to assay. Obviously the most important quantitative trait is grain yield or for areas where wheat is used as a forage, forage yield. However, other important traits include end-use quality and other grain characteristics. In addition, many qualitative traits are modified by minor genes that are most easily selected in later generations. Wheat breeders would select first for grain yield and once they have selected the acceptable group of lines, would then begin the evaluation for end-use quality which is a more expensive and limiting assay.

Selection for end-use quality is extremely important for wheat being used as a food grain. Each end use has its own characteristics and needs, and hence its own selection techniques. The techniques will vary with the amount of seed available, the number of lines that need to be tested, and the importance of the lines. For example, in hard wheats used for bread, the first quality test could be determining protein content to eliminate lines that are too low in protein (less than 12.5%) to produce a good loaf of bread. Thousands of lines can be assayed inexpensively for protein content. As the number of lines are reduced, the lines could be rated using a mixograph which measures some of the bread dough properties and estimates protein quality (as opposed to protein quantity). The mixograph assay requires 10 g of flour; hence, each sample must be micromilled before it can be assayed. As the micromilling and mixograph assay both require more time and grain than the protein content assay, they are usually done only on more advanced lines. After further selection, fewer advanced lines will be milled and baked into loaves of bread. For this rating procedure, often 1000 g of grain is needed and two loaves are baked. Most breeding programs do not have 1000 g of grain of breeding lines until later generations and would usually evaluate by baking a loaf of bread only for 100–200 highly selected lines. As a line is considered for release, it may be evaluated by commercial millers and bakers to see how it performs in their various baking processes. Often fewer than 20 lines per year are evaluated commercially prior to release as commercial wheat cultivars.

Similar to the hierarchy of end-use quality assays, there is one for most other traits. For example, in early generations it may be easy to artificially inoculate wheat plants for leaf (*Puccinia recondita*), stripe (*P. striiformis*), or stem (*P. graminis*) rust which can be readily evaluated visually. In later generations when there are fewer lines, diseases that are more difficult to evaluate, such as root rots or some viral diseases, may be undertaken.

From the above description, it should be clear that most wheat breeding programs begin with literally thousands of lines. By selection, the lines are gradually reduced to very few that may be released. In the initial stages of selection, most lines are selected visually or by using very inexpensive and quick assays. As the number of lines are reduced and more is known about them, more complicated and expensive assays are used (i.e., replicated yield trials, disease and insect screening, end-use quality). The very best breeding programs may release one new cultivar a year.

V. Evaluation

The final process of selection is extensive evaluation of promising experimental lines. The purpose of evaluation nurseries is to determine the areas of adaptation of a new line. Wheat is the most widely grown crop in the world and it is important that producers know where new cultivars should and should not be grown. Hence, the evaluation nurseries should represent the diverse growing conditions that may be found within the region for which the wheat breeding program is attempting to produce new cultivars. As opposed to selection nurseries which attempt to magnify differences among lines so as to make selection easier, evaluation nurseries attempt to very accurately and precisely determine how a line will perform under normal conditions.

The evaluation trials will involve replicated field trials and often complex statistics to determine which lines are similar and which are different. The nurseries will use standard procedures or those that are believed to be possible in the future for land preparation, planting, and harvesting. As it is unlikely that all of the possible environments will be represented in one year, wheat breeders often collaborate in testing advanced lines in regional or international yield trials. For example, wheat experimental lines developed in Texas may be tested in Nebraska to more fully evaluate their winterhardiness or lines developed in Nebraska may be tested in Kansas where there is greater incidence of soil borne viruses and leaf rust than in Nebraska.

By the time an experimental line is released, it is not unusual for it to be evaluated for more than 6 years in multiple locations in a region and have data from over 100 replicated breeding trials. Even with all of these data, it is common for new information to be obtained after the cultivar is released.

VI. The Decision to Release a Wheat Cultivar

The general practice for determining whether an experimental line should be released is that it must be superior to already released cultivars for at least one important trait. Often the superiority is for yield as that is the primary determinant of crop value. However, improved disease or insect resistance or superior stress tolerance or end-use quality also may be the deciding factors for releasing a cultivar.

In some countries, particularly European countries, there are national cultivar release boards that determine if an experimental line should be released. This is often based on national yield trials and end-use quality evaluation. In the United States, the main wheat breeding programs are at land-grant universities and commercial companies. The land-grant universities have generally accepted procedures for cultivar release and each university will decide if an experimental line developed by the university should be released. For commercial breeding programs, the decision to release a cultivar will be made jointly by their research and marketing teams. There is no national wheat board in the United States that determines if an experimental line can be released as a cultivar.

As there are great differences among countries for release procedures, there are also widely differing laws regulating the sale and shipment of seed. The strictest laws for seed sales are in Europe where most wheat breeders are affiliated with commercial companies and where new seed is purchased annually by the growers. In the United States, wheat cultivars may be protected by the Plant Variety Protection Act. This law is important because it allows the wheat breeder and his or her breeding institution to require that the seed be sold by name and as a class of certified seed. The certified seed classes are foundation, registered, and certified seed.

VII. Wheat Seed in the Marketplace

Grain is the common term for wheat seed that is sold for making products or feeding to animals. The term wheat seed is usually used only for seed that will be planted. When a wheat breeder determines that an advanced line has potential to be released as a cultivar, he or she begins increasing the seed. This seed is known as breeders seed and is usually less than 100 kg. Breeder seed should be the purest seed. The breeder seed is used to produce foundation seed. Foundation seed is the purest commercial seed and is used to produce registered seed. Registered seed is used to produce certified seed which is the commonly sold seed purchased by the farmer. Each time the seed is planted, between 40 and 60 times more seed is harvested. Hence, from the 100 kg of breeder seed, 4000 to 6000 kg of foundation seed can be produced which in turn can produce 160,000 to 360,000 kg of registered seed which in turn can produce 6,400,000 to 21,600,000 kg of certified seed. The 21,600,000 kg of seed took 4 years to produce and will plant between 200,000 and 400,000 ha which would represent 15 to 30% of the wheat hectarage in Nebraska. Hence, not only does it take 7 or more years to develop a spring wheat cultivar and 10 to 12 years to develop a winter wheat cultivar, it takes 4 years to produce enough seed to have a commercial impact. To shorten this time, most breeders increase a number of lines every year in hopes that one will be eventually released.

VIII. The Future of Wheat Breeding

As described, wheat breeding has five phases: defining an objective, identifying and incorporating useful genetic variation, inbreeding and selecting among the variants, evaluating the selected lines, and releasing a new cultivar. New technologies will change wheat breeding if they can affect one of these five processes. Genetic engineering, the transfer of a gene(s) from one organism to another or the same organism without having sexual hybridization, has the potential to greatly expand the germplasm available to wheat breeders. Literally the complete biosphere becomes the gene pool for wheat breeding. Similarly, the ability to modify genes, change how they are regulated, or change the amount of product they make will expand the gene pool.

Selection will be aided by improved genetic assays such as restriction fragment length polymorphisms or isozymes that are tightly linked to the genes of interest. Already, a very quick isozyme assay is used to identify a resistance gene for a root rotting fungus. Testing plants for resistance to the fungus is very imprecise as well as being very time and labor consuming. Selection will also be aided by improved statistical techniques to determine differences and similarities among lines and by better abilities to store and retrieve previous information. Statistics is one of the foundations of plant breeding and improved computers and software will greatly improve breeding efficiency. The already mentioned doubled haploid methods have promise in speeding the inbreeding process. However, evaluation procedures and the decision process to release a cultivar will probably not change. To determine how an advanced line performs in a region, it must be adequately tested in that region before it can be released as a new cultivar.

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Wheat Processing and Utilization

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Glossary

Breadmaking Conversion of wheat flour into yeast-leavened bread in a straight dough, sponge and dough, or liquid fermentation process

Extrusion process Process of conversion of cereal products into pasta, instant and infant foods, breakfast foods, pet foods, feeds, and cereals for industrial uses

Flour fractionation Separation of wheat flour into protein-rich and starch-rich fractions by air-classification following pin milling

Industrial products Use of cereal grains or their fractions into materials for chemical base materials, modified products, or energy sources

Wheat milling Process of converting wheat into milled products: flour, shorts, bran, and germ

This article reviews various aspects of wheat processing and utilization: Included are wheat milling (roller milling; selection, blending, and cleaning; conditioning; breaking, sieving, and purification; reduction milling; flour grades and yields, and fractionation); breadmaking (the role of flour; additives and fermentation); soft wheat products (cookies and crackers; cakes; and doughnuts); extrusion products (pasta and extrusion cooking); and industrial uses.

I. Wheat Milling

Most harvested wheat is processed for food. The main use of wheat for food is the manufacture of flour for making bread, biscuits, pastry products, and semolina and farina for alimentary pastes. A small portion is converted into breakfast cereals. Industrial uses of wheat include the manufacture of malt, potable spirits, starch, gluten, pastes, and core binders. Some wheat flour (mainly low-grade clears) is used to manufacture wheat starch as a by-product of viable (functionally in bread making) gluten. The gluten is used to supplement flour proteins in specialty baked goods (hamburger buns, hot-dog buns, hearth-type breads, specialty breads, etc.) and as a raw material for the manufacture of monosodium glutamate, which is used to accentuate the flavors of foods. Some low-grade flours are used in the manufacture of pastes for bookbinding and paper hanging, in the manufacture of plywood adhesives, and in iron foundries as a core binder in the preparation of molds for castings.

In wheat and flour technology, the term "quality" denotes the suitability of the material for some particular end use. It has no reference to nutritional attributes. Thus, the high-protein hard wheat flour is of good bread-making quality but is inferior to soft wheat flours for chemically leavened products such as biscuits, cakes, and pastry.

The miller desires a wheat that mills easily and gives a high flour yield. Wheat kernels should be plump and uniformly large for ready separation of foreign materials without undue loss of millable wheat. The wheat should produce a high yield of flour with maximum and clean separation from the bran and germ without excessive consumption of power. [*See* WHEAT GENETICS AND BREEDING.]

A. Roller Milling—General

In the production of white flour, the objective is to separate the starchy endosperm of the grain from the bran and germ. The separated endosperm is pulverized. A partial separation of the starchy endosperm is possible because its physical properties differ from those of the fibrous pericarp and oily germ. Bran is tough because of its high fiber content, but the starchy endosperm is friable. The germ, because of its high oil content, flakes when passed between smooth rolls. In addition, the particles from various parts of the wheat kernel differ in density. This makes their separation possible by using air currents. The differences in friability of the bran and the starchy endosperm are enhanced by wheat conditioning, which involves adding water before wheat is milled. The addition of water toughens the bran and mellows the endosperm. The milling process comprises a gradual reduction in particle size, first between corrugated break rolls and later between smooth reduction rolls. The separation is empirical and not quantitative. The milling process results in the production of many streams of flour and offals that can be combined in different ways to produce different grades of flour.

Wheat flour production involves wheat selection and blending, cleaning, conditioning, breaking, bolting or sieving, purification, reduction, and treatment (bleaching, enrichment, supplementation). An outline of the wheat milling process is shown in Fig. 1.

B. Selection, Blending, and Cleaning

The miller must produce a flour with definite characteristics and meet certain specifications for a particular market. The most critical requirement is maintaining a uniform product from a product (wheat) that may show a wide range of characteristics and composition. Consequently, selection of wheats and binning according to quality for proper blending are essential phases of modern milling.

Wheat contains many impurities that can be removed by specialized machines. Preliminary cleaning involves the use of sieves, air blasts, and disc separators. This is followed by dry scouring in which the wheat is forced against a perforated iron casting by beaters fixed to a rapidly revolving drum. This removes foreign materials in the crease of the kernel and in the brush hairs. A few mills are equipped with washers in which the wheat is scrubbed under a flowing stream of water.

C. Conditioning

In this process water is added and allowed to stand for up to 24 hr to secure maximum toughening of the bran with optimum mellowing of the starchy endosperm. The quantity of added water increases with decreasing moisture content of the wheat, with increasing vitreousness, and with increasing plumpness. Generally, hard wheats are tempered to 15–16% moisture and soft wheats to 14–15% moisture. In the customary conditioning, the wheat is scoured again, after it has been held in the tempering bins for several hours. A second small addition of 0.5% water is made about 20–60 min before the wheat goes to the rolls.

D. Breaking

The first part of the grinding process is carried out on corrugated rolls (break rolls), usually 24–30 in. long and 9 in. in diameter. Each stand has two pairs of rolls, which turn in opposite directions at a differential speed of about 2.5:1. In the first break rolls there are usually 10–12 corrugations per inch. This number increases to 26–28 corrugations on the fifth break roll. The first break rolls are spaced so that the wheat is crushed and only a small quantity of white flour is produced. After sieving, the coarsest material is conveyed to the second break rolls. The second break rolls are set a little closer than the first break rolls so that the material is crushed finer and more endosperm particles are released. This process of grinding and sifting is repeated up to six times. The material going to each succeeding break contains less and less endosperm.

E. Sieving and Purification

After each grinding step, the crushed material is conveyed to a sifter fitted with a series of sloping sieves. The process results in separation of three classes of material: (1) coarse fragments, which are fed to the next break until only bran remains; (2) flour, or fine particles, which pass through the finest (flour) sieve; and (3) intermediate granular particles, which are called middlings.

The middlings consist of fragments of endosperm, small pieces of bran, and released embryos. The bran-rich material is removed from the middlings in purifiers. Purifiers also produce a further classification of middlings according to size and complete the work of the sifters. An upward air current through the sieve draws off light material to dust collectors and holds bran particles on the surface of the moving middlings so that they drift over to the tail of the sieve.

F. Reduction

The purified and classified middlings are gradually pulverized to flour between smooth reduction rolls,

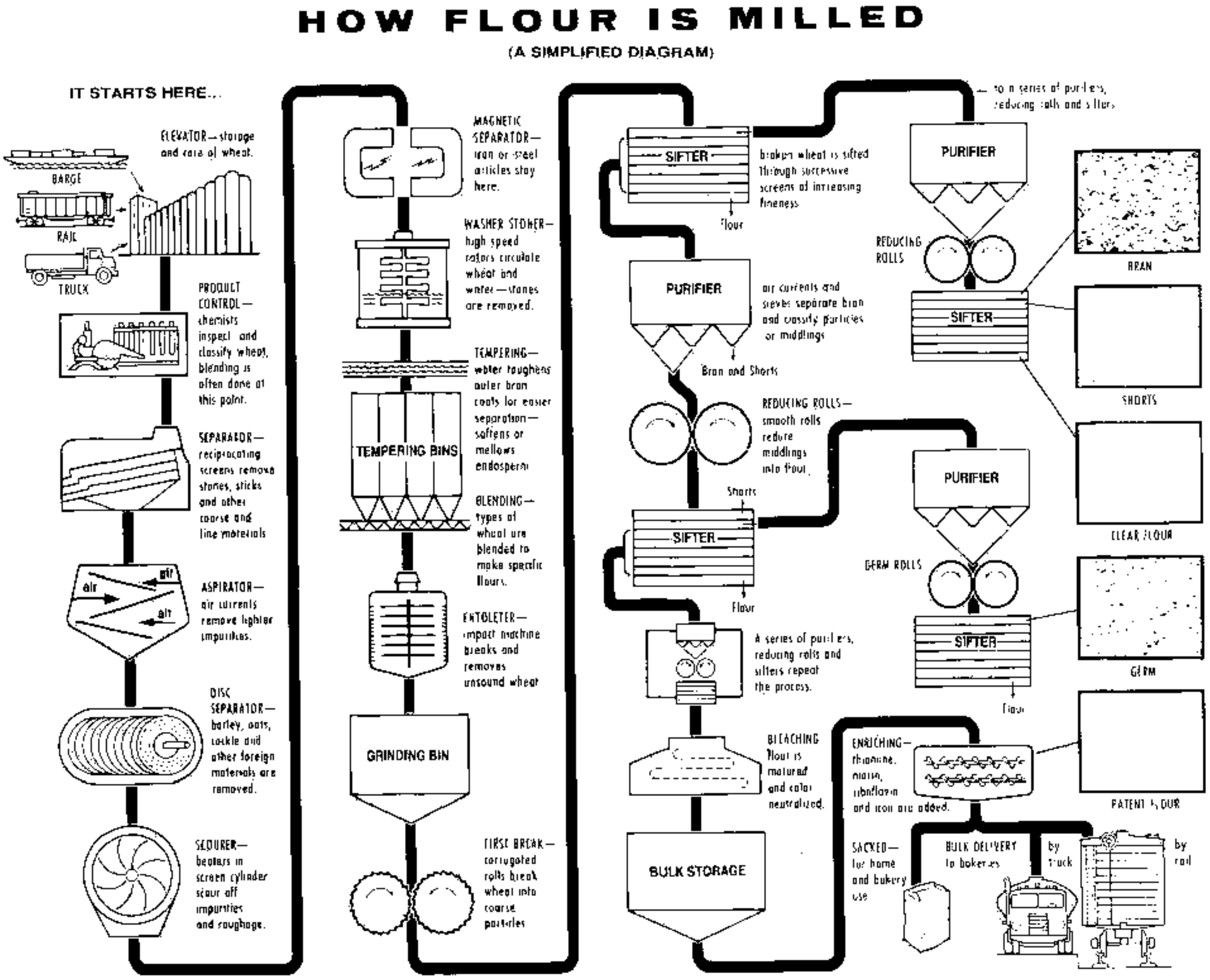

FIGURE 1 Milling process of flour. (*Source:* Wheat Flour Institute, Chicago.)

which revolve at a differential of about 1.5:1. The space between the rolls is adjusted to the granulation of the middlings. The endosperm fragments passing through the rolls are reduced to finer middlings and flour. The remaining fibrous fragments of bran are flaked or flattened. After each reduction step, the resulting stock is sifted. These steps are repeated until most of the endosperm has been converted to flour and most of the bran has been removed as offal by the reduction sifters.

The embryos are largely released by the break system and appear as lemon-yellow particles in some of the coarser middling streams. The embryos are separated as flakes during sieving. Germ may be separated by gravity also. Previously, all the germ was mixed with the shorts as feed. Some special uses of germ in foods and as a source of pharmaceuticals have been developed.

G. Flour Grades and Yields of Mill Products

Each grinding and sieving operation produces flour. With each successive reduction, the flour contains more pulverized bran and germ. The flour from the last reduction, called "red dog," is dark in color and high in components originating from the bran and germ, such as ash, fiber, pentosans, lipids, sugars, and vitamins. Such flour is mostly sold as feed flour.

In a large mill there may be 30 or more streams that vary widely in composition. If all the streams are combined, the product is called straight flour. A straight flour extraction means, generally, a 75% flour, because wheat milling yields about 75% white flour and about 25% feed products. Frequently, the white streams are taken off and sold separately as patent flours; the remaining streams, which contain some bran and germ, are called clear flours. A diagram of flours and milled feed products is given in Fig. 2.

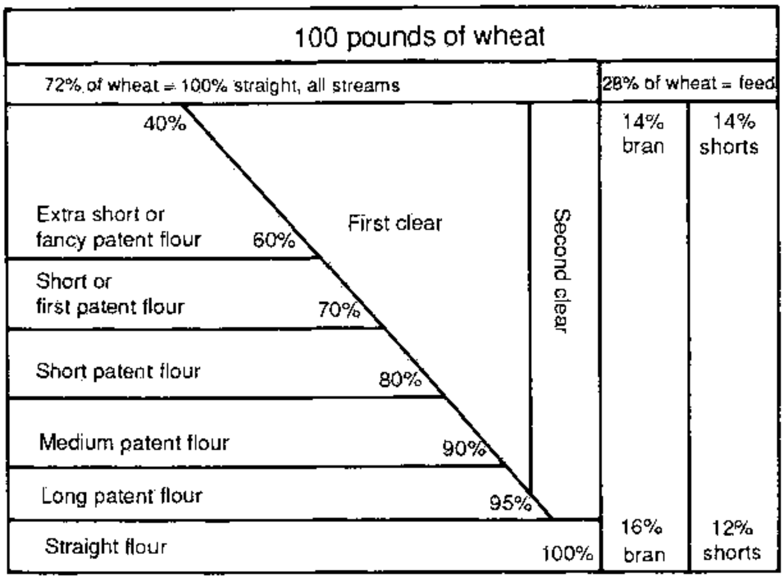

FIGURE 2 Grades of flour (*Source:* C. O. Swanson, Kansas State University, Manhattan, KS.)

Some lighter, clear flours are used in blends with rye and/or whole wheat flours in the production of specialty breads. The darker grades of clear flours are used in the manufacture of gluten, starch, monosodium glutamate, and pet foods.

The plump wheat grain consists of about 83% endosperm, 15% bran, and 2.5% germ. These three structures are not separated completely, however, in the milling process. The yield of total flour ranges from 72 to 75%, and the flour contains little bran and germ. In ordinary milling processes only about 0.25% of the germ is recovered. Bran ranges from 12 to 16% of the wheat milled. The remaining by-products are shorts.

H. Flour Fractionation

Wheat flour produced by conventional roller milling contains particles of different sizes (from 1 to 150 μm) (Fig. 3). The flour can be ground, pin-milled to avoid excessive starch damage, to fine particles in which the protein is freed from the starch. The pin-milled flour is then passed through an air classifier. A fine fraction, made up of particles about 40 μm and smaller, is removed and passed through a second air classifier. Particles of about 20 μm and smaller are separated; they comprise about 10% of the original flour and contain up to about twice the protein of the unfractionated flour. This high-protein flour is used to fortify low-protein bread flours or for enrichment in the production of specialty baked goods. A comparable fraction containing about half the protein content of the unfractionated flour is also obtainable.

I. Soft Wheat Milling

Soft wheats are milled by the method of gradual reduction, similar to the method for milling hard bread wheats. Patent flours containing 7–9% protein, milled from soft red winter wheats, are suitable for chemically leavened biscuits and hot breads. Mixtures of soft wheats are used to make flours for use in cookie and cake making; such flours usually contain 8% protein or less and are milled to very short patents (about 30%). Treatment with heavy dosages of chlorine lower the pH to about 5.1–5.3, weaken the gluten, and facilitate the production of short pastry.

J. Durum Wheat Milling

In durum milling, the objective is the production of a maximum yield of highly purified semolina. Durum wheat milling involves cleaning and conditioning of the grain, light grinding, and extensive purification. The cleaning, breaking, sizing, and purifying systems are much more elaborate and extensive than in flour mills. On the other hand, the reduction system is shorter in durum mills, because the primary product is removed and finished in the granular condition. The break system is extensive to permit lighter and more gradual grinding than in flour mills. Durum wheat of good milling quality normally yields about 62% semolina, 16% clear flour, and 22% feeds.

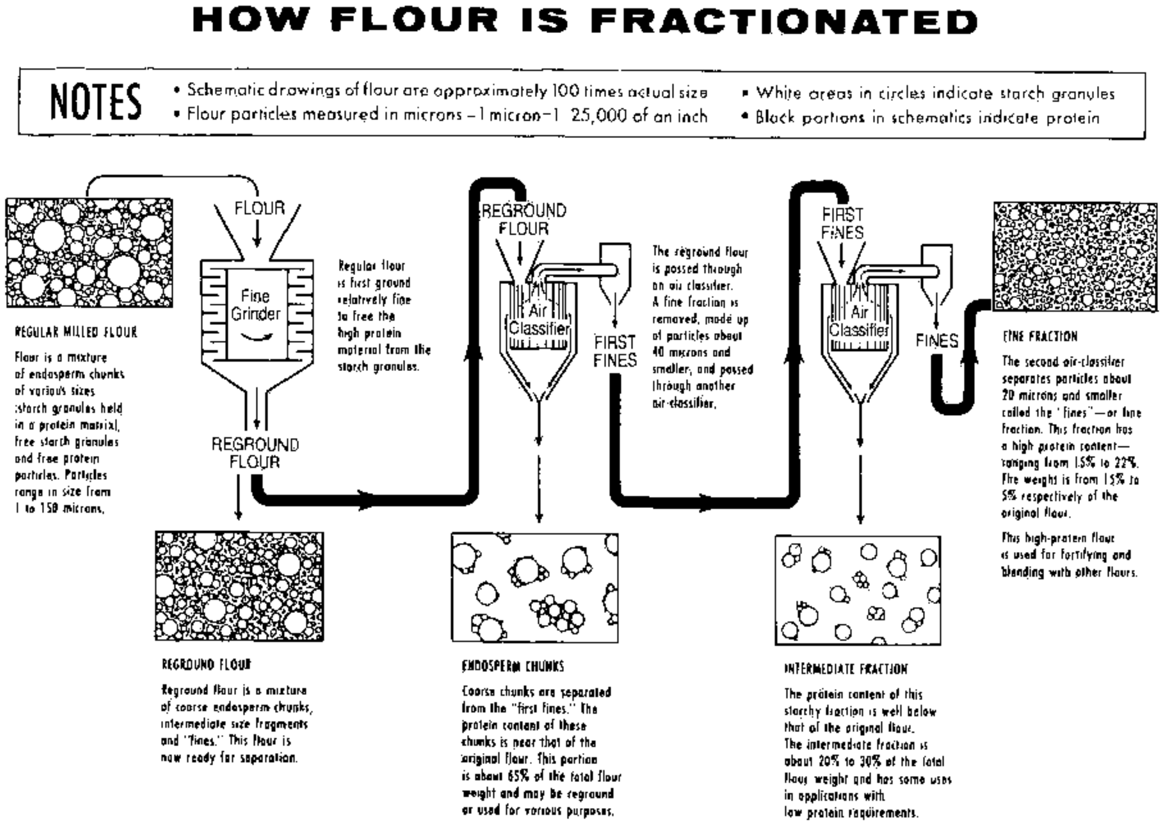

FIGURE 3 How flour is fractionated. (*Source:* Wheat Flour Institute, Chicago.)

Proximate chemical composition of a commercial mill mix of hard red spring wheat and its principal milled products is given in Table I. Table II shows the average nutritional value of 100-g milled products in West Germany.

II. Breadmaking

The production of baked goods comprises the following steps: (1) preparation of raw materials (selection, preparation, and scaling of ingredients); (2) dough formation and development; (3) dough processing (fermentation and leavening, dividing, molding, and shaping); (4) baking; and (5) manufacture to finish products (including measures to retain quality, slicing, packaging, sterilization, etc.).

A. Flour

Although bread has been produced from meals and flours milled from most cereal grains, the type of bread accepted by the customer in the Western world is normally prepared from wheat meal or flour or from wheat-type meals or flours. Flour used in bread making is generally milled from common (or so-called vulgare) wheat. Flour from durum wheat is used in some parts of the world (mainly the Middle East) to make flat bread. In the Western world, durum is used mainly to make semolina for pasta production.

Bread-making quality of a flour depends on the quality and quantity of the flour proteins. Proteins of flours milled from common wheat possess the unique and distinctive property of forming gluten when wetted and mixed with water. It is gluten formation, rather than any distinctive nutritive property, that gives wheat its prominence in the diet.

When water is added to wheat flour and mixed, the water-insoluble proteins hydrate and form gluten, a complex and coherent mass in which starch, added yeast, and other dough components are imbedded. Thus, the gluten is, in reality, the skeleton or framework of wheat-flour dough and is responsible for gas retention, which makes production of light leavened products possible. [*See* FOOD BIOCHEMISTRY: PROTEINS, ENZYMES, AND ENZYME INHIBITORS.]

On the basis of their suitability to produce yeast-leavened bread, wheats and flours are classified

TABLE I

Proximate Chemical Composition[a] of a Commercial Mill Mix of Hard Red Spring Wheat and Its Principal Mill Products

Product	Proportion of wheat (%)	Protein[b] (%)	Fat (%)	Ash (%)	Starch (%)	Pentosans (%)	Total sugars[c] (%)
Wheat	100.0	15.3	1.9	1.85	53.0	5.2	2.6
Patent flour	65.3	14.2	0.9	0.42	66.7	1.6	1.2
First-clear flour	5.2	15.2	1.4	0.65	63.1	2.0	1.4
Second-clear flour	3.2	18.1	2.4	1.41	56.3	2.6	2.1
Red dog flour	1.3	18.5	3.8	2.71	41.4	4.5	4.6
Shorts	8.4	18.5	5.2	5.00	19.3	13.8	6.7
Bran	16.4	16.7	4.6	6.50	11.7	18.1	5.5
Germ	0.2	30.9	12.6	4.30	10.0	3.7	16.6

Source: USDA mimeographed publication ACE-189 (1942).

[a] 13.5% moisture basis.

[b] Nitrogen × 5.7.

[c] Expressed as glucose.

broadly into two groups, strong and weak. Strong flours contain a relatively high percentage of proteins that form a tenacious, elastic gluten of good gas-retaining properties and are capable of being baked into well-risen, shapely loaves that possess good crumb grain and texture. They require considerable water to make a dough of proper consistency to give a high yield of bread. The doughs have good handling properties and are not critical in their mixing and fermentation requirements. They yield good bread over a wide range of baking conditions and have good fermentation tolerance.

In contrast, weak flours have a relatively low protein content and form weak gluten of low elasticity and poor gas-retaining properties. They have relatively low water-absorbing capacity, yield doughs of inferior handling quality, and have mixing and fermentation requirements that render them more likely to fail in baking. Weak flours require less mixing and fermentation than strong flours to give optimum baking results.

B. Other Ingredients

The amount of water added during dough mixing depends on water absorption of the flour, the method and equipment used to make and process the dough, and the characteristics desired in the baked bread. Water is added to bind dough ingredients into a coherent mass, to dissolve certain ingredients (i.e., sugars, soluble proteins, and pentosans), for development of yeast and/or sour dough microorganisms, and for leavening action at the baking stage.

Salt is added (about 1.5% of flour weight) for taste and to improve dough handling. Salt slows down water imbibition and swelling of flour proteins, shortens the gluten, reduces dough extensibility, and improves gas retention, bread crumb grain, and slicing

TABLE II

Average Nutritional Value of 100-g Milled Products

	Main nutrients (g)			Energy		Minerals/mg				Vitamins		
Milled product and type	Proteins	Fat	Carbohydrates	Calories (kcal)	Joules (kJ)	K	Ca	P	Fe	B_1 (μg)	B_2 (μg	Niacin (mg)
Wheat flour, 550	10.6	1.1	74.0	348	1480	126	16	95	1.1	110	80	0.5
Wheat flour, 1050	12.1	1.8	71.2	349	1485	203	14	232	2.8	330	100	2.0
Wheat meal, 1700	12.1	2.1	69.4	345	1465	290	41	372	3.3	360	170	5.0
Rye flour, 997	7.4	1.1	75.6	342	1453	240	31	180	2.3	190	110	0.8
Rye meal, 1800	10.8	1.5	70.1	337	1432	439	23	362	3.3	300	140	2.9

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properties. The amount of yeast is about 2% (flour basis) in regular white bread; for rolls, larger amounts of yeast are used. Bakers' yeast ferments the available sugars (in flour or added) to yield carbon dioxide (and alcohol) to provide light, porous, yeast-leavened products.

Bread can be produced from flour, water, salt, and yeast and/or sour dough. Optional ingredients include fats or oils, sugars, milk powder or mixtures of vegetable (i.e., soy flour) proteins and whey proteins, oxidants, enzymic supplements, dough conditioners, dough softeners, and others.

Figure 4 compares the loaf volumes of breads made from good- and poor-quality wheat flours and very lean to optimized formulations.

C. Fermentation

Bread-making processes can be divided into those that depend on biological and those that depend on mechanical dough development. In processes that employ a biological dough development in production of wheat breads, the effect of yeast development is critical. The main biological processes include the following.

Straight dough. The dough is prepared by incorporating all ingredients in a single stage, and fermentation is carried out in bulk.

Sponge and dough process. Bread dough is prepared in two stages (see Fig. 5).

Liquid ferment process. A liquid ferment contains the essential ingredients for yeast growth (with or without wheat flour) and after fermentation constitutes all or part of the dough liquor.

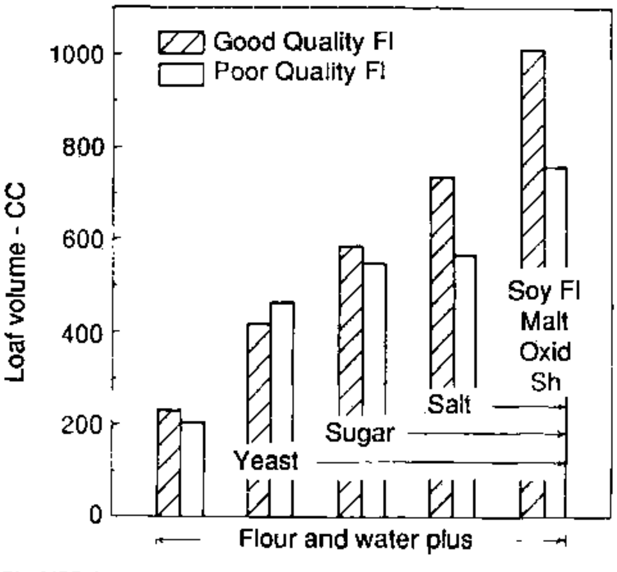

FIGURE 4 Loaf volumes of breads made from good- and poor-quality wheat flours (100 g) and very lean to optimized formulations (including soy flour and additive for oxidation of sulfhydryl-SH-groups). [From Finney, K. F. (1978). *In* "Cereals 78: Better Nutrition for World's Millions." (Y. Pomeranz, ed.). Am. Assoc. Cereal Chemists, St. Paul, MN.]

In processes employing mechanical dough development, traditional bulk fermentation can be replaced by intense mechanical energy input to a dough.

III. Soft Wheat Products

Low extraction, low protein soft wheat flours are uniquely suited for the production of cookies (biscuits), most cakes, wafers, cake doughnuts, and similar baked products.

A. Cookies and Crackers

A high ratio of spread to thickness (W/T) is used as criterion of adequacy of cookie flour. Whereas weak, low-protein soft wheat flours have a W/T ratio of 8.5–10.0, strong, high-protein, hard wheat flours

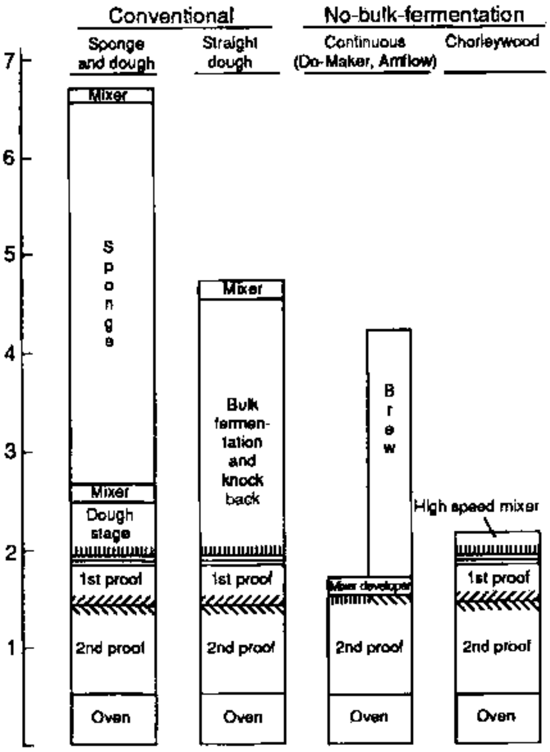

FIGURE 5 Comparison of processing stages and times for two conventional and two no-bulk-fermentation bread-making methods [From Tipples, K. H. (1967). *Bakers Digest* **41(3),** 18–20.]

have a ratio of 6.5–8.0. The main types of cookies, depending on their production methods, are wire cut, rotary, and deposit.

B. Cakes

Most cakes are prepared from batters rather than doughs. The distinguishing differences between the two are summarized in Table III. High-quality cakes should have a large volume, fine grain, and a moist, tender crumb. The flour used for their production is milled from low-protein soft wheats. Chlorine treatment makes it possible to produce sponge cakes with more even crumb texture, increased volume, and greater symmetry. Chlorinated flours are used in layer, genoese, yellow, madeira, and fruit cakes made with greater proportions of sugar and liquor (so-called "high-ratio" cakes).

C. Doughnuts

Production of cake doughnuts is one of the most critical baking processes. The cake doughnut is the only item produced in the bakery that does not have some mechanical means of forming the dough piece into the desired product. The fluid–viscous batter is deposited into the frying fat. It depends on the flow and characteristics of this batter in the fluid medium to flow, fry and set in the desired size and shape.

In general, a doughnut mix contains 55–65% flour (mix weight basis) of 9–10% protein to yield the proper tenderness–structuring profile. Sugar in the range of 22–30% is added to sweeten, tenderize, aid moisture retention, accelerate crust formation, and effect spreading in the fryer. Some shortening, 3–9%, is also included to aid tenderness, increase shelf life, and lubricate the protein structure for proper flour performance. Dried egg yolks (0.5–3.0%) provide richness and tenderness, and 3–5% nonfat milk solids act as a binder and structure builder and contribute to crust color, shelf life, gas retention, and "crowning." Leaveners (1.75–3%) are usually blends of fast-acting sodium pyrophosphate and slower-acting sodium aluminum phosphate, monocalcium phosphate, and sodium bicarbonate. Sometimes, glucono-δ-lactone may be used.

TABLE III

Distinguishing Characteristics of Doughs and Batters

Characteristics	Dough	Batter
Basic ingredients in recipe	Flour, sugar, fat	Sugar, eggs, fat, flour
Processing	Kneading, mixing	Beating, stirring, mixing, short heating
Raising	Biological, chemical, physical	Chemical, physical
Factors affecting binding of water or consistency	Wheat gluten, pentosans, damaged starch, swelling agents	Eggs, fat, sugar, damaged starch, and in part wheat gluten and swelling agents
Consistency	Elastic to plastic	Foamy, soft-plastic, pastelike to semifluid

Source: Menger and Bretschneider, 1972.

IV. Extrusion Products

Cereals can be processed into foods by extrusion. Regular extrusion is used primarily for the production of alimentary pastes. More recently, high-temperature, short-time (HTST) extrusion is used to produce instant and infant foods, expanded pet foods, feeds, and cereals for industrial uses.

A. Pasta

The basic raw material for the production of high-quality pasta products is semolina from durum wheat. Hard durum wheat has a tough, horny endosperm. Semolina from durum wheat requires less water to form a dough and produces a translucent pasta product of acceptable cooking and eating properties. A variety of pasta products can, however, be manufactured from a wide range of wheats milled to various granulations.

Commercial semolina should pass through a U.S. No. 20 sieve and should contain a maximum of 3% flour (passing through a No. 100 sieve). A uniform fine particle size is specified. According to FDA standards of identity, egg noodles and egg spaghetti must contain 5.5% egg solids, by weight, in the final product. Optional ingredients (in specific maximum amounts) include seasonings, enrichment (minerals and vitamins), soy flour and soy protein, vegetables, and gluten. In commercial practice, alimentary pastes are formed by extrusion on large automatic machines (capacities up to 1500 lb per hour) that perform several operations. Material flow in the processing of pasta products is depicted in Fig. 6. Water is added (along with other ingredients) to make a stiff dough with

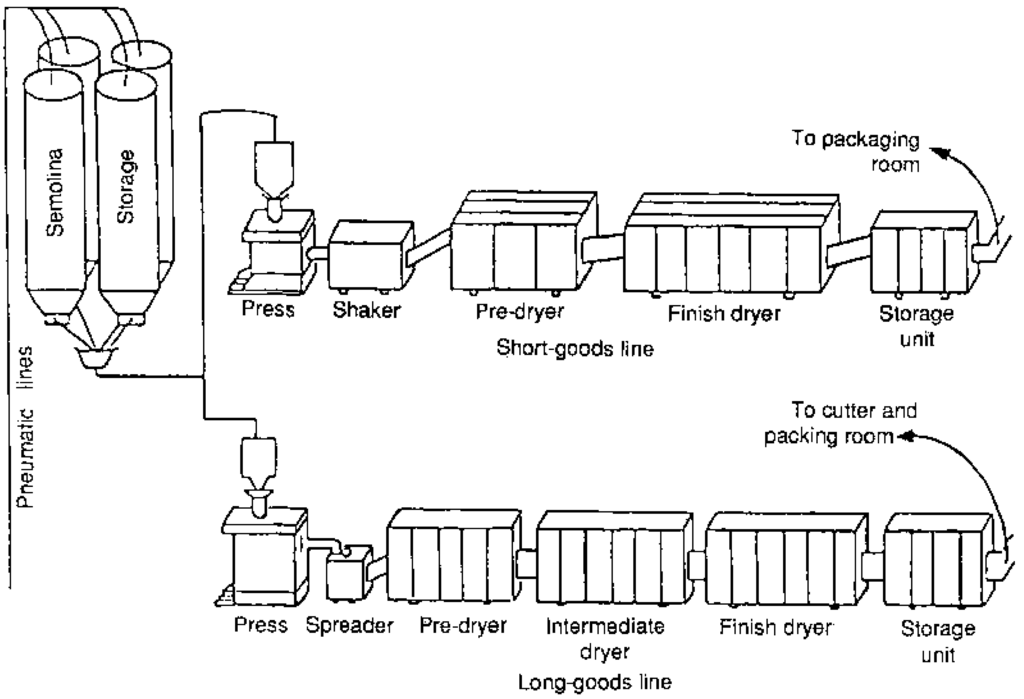

FIGURE 6 Material flow in the processing of pasta products. [From Fraase, R. G., Walsh, D. E., and Anderson, D. E. (1974). An analysis of the economic feasibility of processing pasta products in North Dakota. Station Bull. ND Agric. Ept. No. 496.]

about 31% water. The dough is forced under pressure through dies of an extrusion auger.

Pasta products marketed in Europe and the western hemisphere include spaghetti—small diameter, solid rods; macaroni—hollow tubes; noodles—flat strips or extruded oval strips; and miscellaneous products—cut by revolving or blade cutters. The various pasta shapes are illustrated in Fig. 7.

B. Extrusion Cooking

An extrusion cooker may be considered as a continuous reactor capable of simultaneous transporting, mixing, shearing, and forming of food materials under elevated temperature and pressure at short resistance times.

The basic components of an HTST extrusion cooking system include (1) continuous, uniform, and controlled feeding of processing materials to the extruder; (2) equipment to precondition the materials with steam at controlled temperatures; (3) uniform application of steam and/or water; (4) an extrusion assembly for process materials; (5) temperature control during the whole process; (6) control of residence time in the extruder to optimize temperature, shear, and agitation; (7) control of exudate shape and size; and (8) availability of equipment to dry, cool, size, and treat the product through the addition of flavors, vitamins, fats, etc. A typical arrangement is shown in Fig. 8. Extrusion can be used for production of foods, feeds (e.g., pet foods, fish feed, and gelatinized cereals for ruminants), and products for industrial purposes (e.g., pregelatinized or modified starches and flours). The extruded foods include breakfast cereals and snacks; fortified cereal extrudates; instant or quick-cooking noodles or pasta; alimentary pastes from nonwheat flours; crackers, wafers, crisp-bread products; extruded flour for baking; and miscellaneous foods.

V. Industrial Uses

Traditionally, cereals are considered food and feed grains. However, large and widespread production beyond the demands of the principal markets have encouraged exploration of industrial uses of cereals. Cereal grains, milled products, and by-products of milling are finding increasing use in a variety of nonfood applications.

About 1 ton of wheat straw is produced along with 1 ton of wheat grain. Total production of straw pulp on a worldwide basis is about 14 million metric tons. By using better collection methods, the straw potential could be increased to 1 billion metric tons. Only

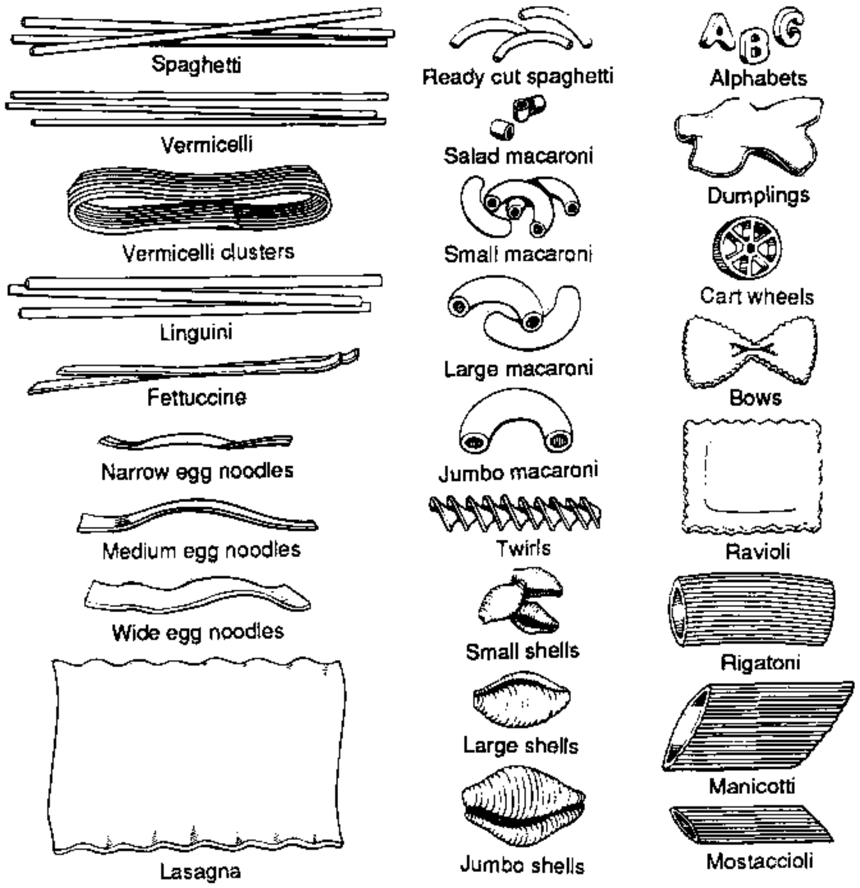

FIGURE 7 Pasta products. (Courtesy of Conagra Co. Ltd., Omaha, NE.)

10% of the world's straw used for pulp production would be about 30 million tons of pulp. Residues and by-products of cereals are excellent sources of furfural, a basic raw material in many industrial technologies.

Cereal biomass can be pyrolyzed to produce sugar, olefinic compounds, charcoal, and gaseous fuel. Carbohydrates can be hydrolyzed to fermentable sugars to make ethanol and then converted into ethylene and butadiene. Biomass can be digested by anaerobic bacteria to produce methane. Biomass can be reacted with carbon monoxide, using heat, pressure, and a catalyst to produce an oil. Lignin can be used to make phenol in benzene production.

Cereal polymers (carbohydrates and proteins) can be converted into monomers, which can provide the raw material and flexibility as basic raw materials. Equally promising are novel uses of undegraded polymers.

Most industrial uses of cereals depend on the properties of the main component, starch, which ranks in many developed countries as a major industrial chemical. Raw materials and technology exist for basing a portion of the chemical industry on four fermentation products: ethanol, isopropanol, *n*-butanol, and 2,3-butanediol. Industrial uses constitute an economic market for grain ethanol, in which the product is competitive with ethanol derived from petroleum and natural-gas liquids.

Wheat or low-grade wheat flours can be separated into many products that find wide applications.

Wheat flours. In paper sizing and coating; as adhesive or laminating mixtures in corrugated box boards, paper bonding, plywood industry, decorative woods and veneers, detergent formulations.

Starch. In paper sizing and coating, fiber or textile finishing, printing mixtures, paper bonding, adhesives, plywood industry, alcohol production.

Gluten. In paper manufacture, surface-active agents, adhesives, monosodium glutamate and glutamic acid, edible and/or soluble packaging fabrics, coatings, gums, sausage casings.

Wheat germ. In production of antibiotics, vitamins, pharmaceuticals, skin conditioners.

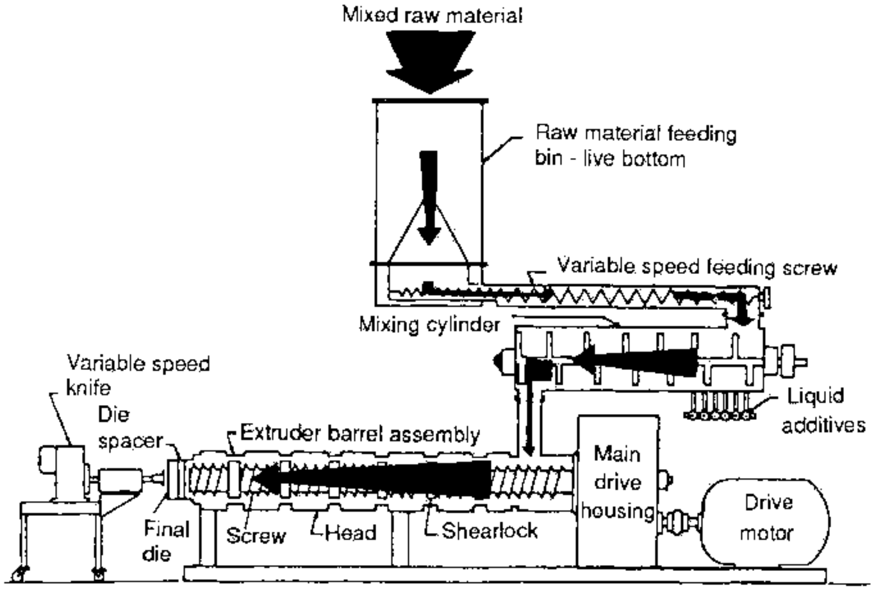

FIGURE 8 Typical arrangement of line bin feeder, preconditioner, HTST extrusion cooker. (Courtesy of Wenger Mfg. Co., Inc., Sabetha, KS; from Smith and Ben-Gera, 1980.)

Wheat bran. In production of furfural, in the production and/or carriers of enzymes, antibiotics, and vitamins.

Residues remaining after the harvest of crops have been proposed as an energy source. Wheat cropping typically produces 2.5 tons of residue per acre. The benefits are limited by high energy costs to collect, transport, and process the residues. The energy to collect 1 ton of wheat straw is 50,500 kcal.

The conversion of glucose to ethanol is represented by the formula:

$$\begin{array}{ll} C_6H_{12}O_6 \rightarrow & 2C_2H_5OH + 2CO_2 \\ 180\text{ g} & 92\text{ g} \\ 673\text{ kcal} & 655\text{ kcal} \\ 12.88\text{ lb} & 1\text{ gal } (84{,}356\text{ BTU}) \end{array}$$

The production of alcohol as a source of fuel has been the subject of many investigations. Some surveys concluded that ethanol production uses more energy than it produces. Differences of opinion on the energy balance derive mainly from variations in interpretation.

The result depends strongly on assumptions about use of crop residues for fuel and the rating of gasohol (a 90:10 mixture of fuel and alcohol). In terms of total nonrenewable energy, gasohol is close to the energy break-even point. On the other hand, in terms of petroleum or petroleum suitable energy, "gasohol" is an energy producer, as most energy inputs into the process can be supplied by nonpetroleum sources like coal.

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Wildlife Management

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Glossary

Climax-adapted species Species adapted to, and dependent upon, habitat resources occurring within a climax biotic community

Climax biotic community Terminal, relatively stable biotic community that results from progressive development of vegetation and soils following land disturbance

Density dependent Correlated with population density, this usually applies to population characteristics, especially rates of reproduction and mortality; generally, reproduction declines and mortality increases with increased density

Density independent Not correlated with population density, especially population characteristics; in particular, weather events and sudden degradation of habitat may cause these stochastic population changes

Habitat resource Any of the food, cover, or other characteristics of a habitat that are used and needed by a wildlife population

Limiting resource Habitat resource that is inadequate, in quantity or quality, for the needs of a wildlife population; the lack of this resource thus limits the size, productivity, or quality of the population

Population density Number of animals in a population relative to the amount of available habitat, or of habitat resources

Species of developmental stages Species adapted to, and dependent upon, habitat resources occurring within temporary stages of biotic succession that follow land disturbance

Wildlife management is practiced to attain the goals of wildlife conservation, which is the wise use of wild lands, plants, and animals. Wildlife management is the art of making land produce valuable populations of wildlife in relatively natural biotic communities. Vertebrate animals are usually emphasized in wildlife management; but it is clear that maintaining suitable environments for wild vertebrates always requires some emphasis on plants and invertebrates as well.

I. Wildlife Values

Wildlife are managed to enhance their positive values to mankind and to minimize their negative values. Positive values include commercial, recreational, biotic, scientific, aesthetic, and social values. Negative values are the damages caused by wildlife to private and public properties and the costs for controlling those damages.

The commercial value of wildlife includes the value of wild animals and their parts (hides, antlers, etc.) to subsistence users and as articles for trade or sale. In addition, diverse entrepreneurs realize profits by providing equipment, lodging, food, transportation, and various services to people who pursue wildlife, usually for recreational purposes. Many rural economies depend upon subsistence and other commercial values from wildlife. The value of wildlife parts, and the value of income to wildlife-related business, may be calculated in dollars to measure commercial value of wildlife.

The recreational value of wildlife consists of the enjoyment, and the physical and mental well-being, that are realized when people hunt, fish, view, or study wildlife. This value may be measured by these recreators' "willingness to pay" for wildlife-related experiences. In countries where wildlife is a publicly owned resource, actual expenses of recreators almost always underestimate willingness to pay. Economists have developed indirect methods for estimating untested willingness to pay and provide a dollar-based measure of recreational value of wildlife for comparisons with other resources.

The contributions of wildlife to maintaining valuable ecosystems constitute a biotic value. Wildlife activities including predation, scavenging, seed dispersal, pollination, and soil tillage contribute to maintaining the diversity of species in ecosystems and may prevent some populations from extirpation or from becoming detrimentally large.

Populations of wild animals are used to study processes including natural selection and evolution, population dynamics, competition, epidemiology, and zoogeography. The resulting knowledge is applied to practical problems and enhances science, education, philosophy, and even religion.

The social value of wildlife consists of benefits accruing to communities. As people realize economic and other values from wildlife, they may become more satisfied, productive, and cooperative members of society. Moreover, communities offering abundant wildlife experiences will attract professionals, including doctors, lawyers, and engineers, who would otherwise practice in more developed and lucrative cities.

The aesthetic value of wildlife is most personal and diverse. It includes the contribution of wildlife to literature, music, and art, as well as the beauty in seeing or hearing wild animals. In addition, as people study and understand wildlife, their aesthetic appreciation is expanded. There is beauty that meets, not only the eye and ear, but also the educated mind.

Wildlife may create problems for mankind. They may consume or damage agricultural crops, destroy livestock, carry disease to livestock or to humans, deface or damage buildings, among other problems. Direct and indirect methods for controlling these damages may be costly. Wildlife causing such damage are labeled "overabundant".

Since wildlife values are so diverse, and may not be measured in any one scale, such as dollars, the total value of a species population, or of a wildlife community, is difficult to measure for comparing the value of wildlife management against other activities. Replacement costs may be used to measure total wildlife value. Thus, the costs of gaining control of, and managing, sufficient habitat to recreate a wildlife resource would be the total value of the wildlife resource.

II. Wildlife Biology

Successful wildlife management depends upon knowledge of the biology, especially ecology, of wildlife species.

A. Habitat Requirements, Limiting Factors

A suitable habitat is the most basic need of every wildlife species. Each species has evolved a unique set of anatomical, behavioral, and physiological adaptations that determine the habitat resources it may exploit and also will require. Moreover, the sexes and age classes of animals may exploit habitat differently, and habitat needs may vary seasonally. Consequently, habitat requirements are unique and numerous for every species. However, all species need foods including water, cover resources, and a suitable geographic distribution of these habitat resources.

Food and cover resources must be suitably juxtaposed on the landscape to allow a species to use those resources. Many species are highly mobile and may migrate seasonally, so that some habitat resources may be far apart. Other species are sedentary, requiring that their habitat resources occur within a limited area. In addition, proximity of resources may benefit a population by allowing resource exploitation with minimal energy expense or minimal exposure to predation.

While a wildlife species population will require several different habitat resources, the quality of animals, and productivity and number of animals, will usually be limited by an insufficiency of only one or a few of those resources. Most habitat resources will not be limiting. Lands containing limiting habitat resources are termed "critical areas." Impacts that diminish resources on critical areas will diminish a population over a much larger area. Also, management to improve a population's habitat must enhance those habitat resources that limit the population. Enhancement of nonlimiting resources is wasted management.

B. Biotic Succession

Vegetation, an important component of wildlife habitats, may change steadily over many years—altering habitat conditions for wildlife. This natural process of vegetative development follows each episode of land disturbance. Disturbance may be natural (fire, windstorm, flood) or human-caused (logging, land-clearing, overgrazing, prescribed fire). Following disturbance, the species composition and structure of vegetation changes until a plant community of relatively stable species composition is attained. This community is termed climax vegetation. Since wild animals depend (indirectly in the case of carnivores) upon vegetation, the species compositions of wildlife communities also change during vegetative succession toward a climax biotic community.

Wildlife that depend upon early stages of vegetative succession are "disturbance-adapted species." Maintenance of their habitat requires periodic disturbance to maintain early stages of plant succession. Wildlife dependant upon climax vegetation are "climax-adapted." Their habitats require protection from natural or human-caused disturbance. Still other wildlife species require a mixture of vegetative stages. Enhancing their habitat may require disturbance or protection, depending upon which needed stage of vegetation is most scarce at a particular time and location and therefore is limiting the species population.

C. Reproduction

Successful reproduction is critical for (1) offsetting natural mortality and maintaining wildlife populations, and (2) producing annual surpluses of those species that are harvested. Some wildlife species have adapted to their normally high rates of natural mortality by having high reproductive potentials. These species, termed *r*-selected (selected for a high rate of population increase), may have large litters or clutches and may breed at an early age and more than once per year. Most are small animals, such as rodents, squirrels, and most birds. Populations of *r*-selected species usually contain a preponderance of young animals because individuals are replaced rapidly. (There is a high turnover rate.) Populations of *r*-selected species may expand rapidly to utilize temporary habitats, such as those occurring following vegetation disturbance. Other wildlife species have adapted to more stable environments by having low reproductive potentials commensurate with normally low rates of natural mortality. These are termed *K*-selected species (selected by conditions existing when a population persists near the carrying capacity, *K*, of the environment). They have small litters or clutches and may breed infrequently and late in life. They are mostly large birds and mammals. Populations of *K*-selected species normally contain mostly old animals and are relatively stable from year to year. The categories of *r*- and *K*-selected species are useful, but not discrete, as wildlife species exhibit a continuum from very *r*-selected (i.e., rabbits) to very *K*-selected (i.e., grizzly bears).

Reproductive success often declines as population size increases (density-dependent reproduction, where density = the number of animals per unit of habitat). Density dependence may result from competition among breeders for habitat resources or from physiological responses to stresses of crowding and competition. Reproductive success may also be influenced by density-independent factors, especially weather that may affect the availabilities of habitat resources or the survival of neonates. Density-independent factors predominately influence reproductive success in *r*-selected species; density-dependent factors are more important in *K*-selected species.

D. Mortality

Wild animals are lost from populations by starvation or malnutrition, natural or human-caused accidents, predation, exposure, diseases, and harvest by man. Mortality rates are sometimes density dependent (a greater proportion of the population dies when the population is larger). Also, density-independent mortality occurs due to stochastic events such as severe weather, outbreaks of some diseases, or sudden destruction of habitat. Predation rates may be density independent or may be either positively or negatively correlated with prey density, depending on habitat conditions and on the ratio of predator abundance to prey abundance.

Density dependence results from habitat carrying capacity. As a population increases toward the maximum number of animals that habitat resources can sustain, an increasing proportion of the population becomes vulnerable to most forms of mortality. Particularly in *r*-selected species, a "doomed surplus" of vulnerable animals is produced annually. Various types of mortality will interact to remove these vulnerable animals. Such mortality factors are compensatory, in that a decline (or increase) of one type of mortality will produce an increase (or decline) of other types of mortality, so that total mortality is unchanged. When harvest by man is compensatory, it is termed "replacive," in that harvest replaces, and does not add to, natural mortality. Harvest is most apt to be replacive for *r*-selected wildlife with high natural rates of population turnover.

For *K*-selected species, such as large mammals, human harvest may be used to limit population size and achieve high rates of (density-dependent) reproduction. Such harvest is more additive than replacive, although the intended limitation of population size may also achieve lowered rates of (density-dependent) natural mortality in the long term.

III. Types of Wildlife

A. Categories Based on Biology

Some wildlife species have evolved anatomical, physiological, and behavioral characteristics for living in unique environments. These **specialized species** are adapted, but also limited, to a narrow range of environmental conditions. They are quickly reduced or eliminated by alteration of habitat. Other wildlife are **generalized species**. They have large geographic ranges, exist in a variety of habitats, and have diverse food habits. Generalized species adapt readily to most habitat changes.

Climax-adapted species are specialized for living in climax vegetation. They are eliminated by disturbance of the climax. Other wildlife are adapted for living in the vegetation of disturbed sites. **Disturbance-adapted species** decline as vegetation develops toward climax. Management of habitat for these species is described above.

Habitat-interior species do not compete well with the many other species that live near the edges of patches of homogeneous vegetation. They only prosper deep within these patches, and large patch size is a habitat need. In contrast, **edge species** prosper with simultaneous access to the habitat resources of two or more vegetation patches. Environments with numerous, small or narrow patches of vegetation favor edge-adapted species.

Relict populations of wildlife occupy isolated, small areas of suitable habitat, often far from the main range of their species. They may be part of a local fauna and flora representing past climatic conditions. Relict populations usually are small and very sensitive to habitat change or to slight increases in mortality rates. As with all small, isolated populations, they may lose genetic diversity through random selection and may experience depressed reproduction or survival due to inbreeding.

B. Categories Based on Status or Habitat

A sharp rise in extinctions, coincident with expansion of industrialized man, is depleting the earth's biotic resources. Reversing this trend will require a system of habitat reserves in each of the planet's biotic regions. Some rare, high-profile species are legally recognized as **threatened by**, or in immediate danger of, extinction. In the United States, classification as **endangered** currently (1994) requires that a rare species be fully protected and that priority be given to its habitat needs in land management.

In contrast, some wildlife thrive in habitats created by man. These populations are **overabundant** if they damage agricultural crops and other property, kill livestock, or spread diseases to domestic animals or humans. Wildlife damage is controlled by direct reduction of offending animals, by barriers and repellents, and by manipulating habitat to remove critical needs of overabundant wildlife.

Wildlife used and enjoyed by people may be emphasized in land management. These **featured species** include those harvested for recreation or subsistence and those especially sought for viewing by recreators. The take of harvested species usually is regulated to maintain a base population and a sustained harvestable surplus. Featured species are also enhanced indirectly by habitat manipulation or habitat protection.

Generalized species, primarily, have adapted to farms and urban areas. Most **farm wildlife** depend upon limited areas of unused habitat such as windbreaks, hedgerows, roadsides, ditchbanks, and retired acres. Extensive monocultures of cropland, often treated with harmful pesticides, produce little wildlife. Likewise **urban wildlife** depend upon vegetated yards, cemeteries, semi-wild parks, and unused floodplains. In contrast, rangelands and forests sustain a greater variety of wildlife. **Rangeland wildlife** are enhanced by good range management including development of water sources, prevention of overgrazing, and protection of riparian sites. The variety of **forest wildlife** in commercial forests will depend upon the intensity of silviculture. Extensive monocultures of even-aged trees sustain few wild species. In multiple use forestry, timber harvests may be used to develop forest types, stand ages, and patch sizes that will provide habitats for many disturbance-adapted species or may optimize habitat for one or a few featured, disturbance-adapted species. [*See* FOREST ECOLOGY; RANGELAND MANAGEMENT AND PLANNING; SILVICULTURE.]

Many species of wildlife have been transplanted between continents or between major biotic regions of continents. Successful transplants are considered **exotic species**. Exotic wildlife have damaged and destroyed native floras and faunas, especially on oceanic islands and in the Australian region, which have been isolated from competition and evolution on the major continents. Elsewhere, transplants of exotic wildlife have brought failures, successes, and some problems. Of many game birds transplanted into the United States, only three persist; and only one, the ring-necked pheasant, is truly successful. In contrast, many transplants of large hooved mammals into the United States have succeeded. Many of these exotic mammals have modest ranges, as they are controlled by hunting; but the number of exotic hooved mammal species exceeds the number of native hooved mammals in the United States.

IV. Population Dynamics

A wildlife population's rate of increase, r, is determined by the component rates of reproduction, mortality, immigration, and emigration. In small populations within large, ideal habitats, r approaches the species' maximum biotic potential. As a population grows toward limits set by habitat carrying capacity, r usually declines in a density-dependent manner. However, stochastic events may cause small or large variation of r. Density dependence usually predominates in large, homeothermic wildlife in good habitats. Density independence is more common in populations of small, especially heterothermic, vertebrates and in populations in poor habitats or near the edges of their geographic ranges. Density dependence of r may be delayed (correlated with past, rather than current, density). Delayed density dependence occurs when characteristics of the population, or its environment, result from population density, but persist temporarily following a change in density. Delayed density dependence causes populations to fluctuate in alternating periods of abundance and scarcity. In a few populations, these fluctuations are regular and termed "cyclic."

Wildlife populations and habitats are monitored to (1) detect unacceptable changes in abundance, population quality, or habitat condition, and (2) evaluate the efficacies of management practices. Monitored population characteristics include reproduction, animal condition, population sex–age composition, and population size and trend. Monitored habitat characteristics include abundance, distribution, and utilization of habitat resources. Obtaining unbiased and suitably precise estimates of these characteristics requires methods and sampling procedures adapted to local conditions. A great variety of estimation methods has been developed.

V. Management Practices

A. Habitat Management

Habitat management includes protection or manipulation of habitat, depending upon goals and upon the needs of targeted wildlife species. Knowledge of species' habitat requirements, of local limiting factors, and of successional affinities of species, cited above, is necessary for effective management. Habitat management may be used to increase or to decrease populations of targeted species. Where a small number of species is targeted, many other wildlife species will also be affected. Some will be enhanced; some reduced; and some precluded. Where biodiversity is a primary goal, management must develop and maintain a diversity of vegetation types, successional stages, and patch sizes. Where wildlife production is secondary to other land uses, such as agriculture or forestry, primary land uses may be modified or limited to sustain moderate populations of featured wildlife species.

B. Population Management

Most harvest for commercial or recreational purposes is regulated by state or federal agencies to assure maintenance of suitable base populations. Timing and length of the harvesting season, daily and seasonal limits, methods of taking, and the species, sex, or ages of animals taken may be manipulated to achieve

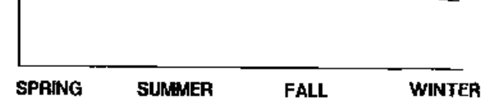

FIGURE 1 Yearly cycle of a population (N) having large recruitment and turnover annually (solid line). Harvest may be applied as replacive mortality without affecting the base population in a subsequent breeding season (dotted line).

harvest goals. Wildlife are also exploited to control overabundant populations.

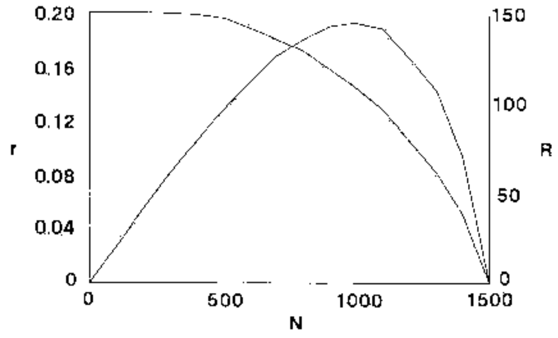

FIGURE 2 Effect of a density-dependent rate of recruitment ($r = R/N$) upon the number of animals recruited (R) to a population (N). In populations with strong density dependence, harvest may be applied as an additive mortality to maintain N at the base population producing the maximum R and maximum harvestable surplus.

For populations of r-selected species (usually small game), in which the determinants of r are largely density independent, there are variable but usually large annual surpluses of animals. Harvests usually are conservative, tend to be replacive mortality, and rarely affect base population size (Fig. 1). For populations in which r is more precisely density dependent (usually big game), harvests are more apt to be additive mortality and may be used to regulate base population size. With a density-dependent r, maintaining a base population somewhat below the carrying capacity of the habitat will maximize the sustained yield of animals per year (Fig. 2).

Wildlife are transplanted to establish populations in unoccupied but suitable ranges and to augment the genetic diversities of small, isolated populations. Rarely, diseases of especially valuable wildlife are controlled by capturing and vaccinating animals or by feeding or injecting drugs to control diseases or parasites.

VI. Wildlife Policy and Administration

Ownership and management of wildlife varies greatly among nations. In the United States, wildlife are the collective property of all the people. Government agencies, as public trustees, manage and protect wildlife. However, much wildlife habitat is privately owned and controlled, creating conflicts between public and private goals.

States have retained responsibilities for managing most wildlife populations within their boundaries. State agencies are highly variable, but usually include programs for regulating recreational and commercial harvests, enforcing wildlife laws, monitoring populations, monitoring and advising on impacts of land uses upon wildlife, public education, and advising landowners on habitat management and on controlling wildlife damage. Policies for most state wildlife agencies are formulated by appointed commissions. Most funding of state programs is derived from sales of hunting and fishing licenses and from taxes on purchases of hunting and fishing equipment.

Several federal agencies manage wildlife habitats on federal lands and are responsible for certain wildlife populations. In particular, threatened and endangered species, migratory waterfowl, and marine fishes and mammals are managed by the federal government, with cooperation from the states. Federal management agencies include the Fish and Wildlife Service, National Park Service, and Bureau of Indian Affairs within the Department of Interior; the Forest Service, Soil Conservation Service, and the Animal and Plant Inspection Service within the Department of Agriculture; and the National Marine Fisheries Service within the Department of Commerce.

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Women in Agriculture

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Glossary

Alienation of land Privatizing land and making it available for sale

Division of labor When productive activities are divided by the characteristics of the workers. In the social division of labor, some people produce one good or service and other people another. In the task division of labor, the production process is broken down into its component tasks, which are assigned to different types of workers

Hacienda Extensive agriculture production system

Mestizo Individual of mixed ancestry; in Latin America, often the progeny of indigenous groups with colonizers

Role Set of expectations governing the behavior of persons holding particular positions in society

Role complementarity When the activities and responsibilities of men and women work together toward common goals without hierarchical implications for the differences

Women have always been active in agriculture. Early archeological data suggest women were the first to domesticate plants, bringing the seeds they had gathered near to their dwellings to be planted and raised on a systematic basis to ensure food supply. Further, it is suggested that women were crucial in the domestication of animals, which in turn contributed toward creating agricultural surplus through the use of animal traction and manure to increase productivity, as well as the products of milk, fiber, and meat provided by the animals themselves. Women's actual agricultural activities have changed dramatically over time, yet women's contributions to agricultural production continue to be of importance. Increased agricultural productivity allowed for the social division of labor and more and more individuals to be freed from the demands of food production, thus creating ruling and warrior classes. Within agriculture, division of labor also occurred.

I. Traditional Division of Labor

Historical accounts of Europe, Africa, Asia, and Latin America all suggest the importance of women in agricultural production. We have evidence from drawings and farm records of women's complementary activities within the feudal system as well as in more independent farming systems and political structures.

A. Role Complementarity

Contemporary anthropological accounts also stress the role complementarity of women in traditional agriculture. In most agriculturally based households, it was crucial that everyone work, young, old, male, and female. The division of labor was based, in part, upon the physical abilities of the individuals, so that the old were spared from extremely heavy work as were the very young. In large measure what work was done by age and gender was culturally determined. What was men's work in one culture, such as, for example, the care of milk cows, was women's work in another culture. Almost always land clearing

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and plowing, which were viewed as heavy work, was a male-dominated activity, but there are cultures in which women engaged in these activities as well.

Roles in agriculture were learned through apprenticeship, which was often gender specific. There were women's knowledge streams and men's knowledge streams. Women, for example, would know how to choose the best seed to save over the hungry season to be planted again for the next harvest, as well as the way to care for small animals to ensure survival of the healthiest when food supply was limited. In Honduras, in an area of recurrent drought where feed is limited, the practice in hog rearing is to let shoats suckle from the sow for the first month. Natural selection occurs, and two-thirds of the shoats die. The shoats that survive the first few months then receive supplemental feed and care. Given the limited resources available, the high shoat mortality is not a problem and, in fact, helps assure that those shoats in which the family production system invests will then survive to adulthood and serve as a source of savings for the family. Animal husbandry and the local knowledge to maximize local resources is often in women's hands.

Further, women often gather herbs and medicines from forested areas. Current studies in a variety of areas suggest that women are able to identify nearly six times as many different species of indigenous plants than are men. This is an important part of maintaining genetic diversity within the biosphere. [*See* LABOR.]

B. Community Interdependence

In more traditional communities, much of agriculture was based on a community division of labor, not just on a family division of labor. Complicated labor exchanges were negotiated by men and by women, often with members of the same sex. Such exchanges involved direct exchanges of labor at times of particular high labor demand, as well as simple gifts, particularly of food, seed, and plant cuttings, that could be utilized to maintain agricultural productivity. Very often women were in charge of the less-formal exchange relationships that were vital in maintaining communities and protecting them from the necessity of becoming totally dependent on the sale of labor. Such informal exchanges helped maintain smallholder agricultural production.

II. Integration into the World System

A. Impacts of Changes in Labor Use

Traditional communities were based on subsistence production with very little for sale. As these communities were penetrated by world markets, the division of labor in agriculture changed dramatically. In much of the colonized world, particularly Africa and Latin America, the first impact on traditional farming systems was the removal of male labor to work in seasonal plantation agriculture. Men were needed for the sugar harvest and the banana harvest. A few women followed to provide the necessary domestic functions of food and laundry. But generally, women remained at home in charge of the subsistence production plots and animal production activities.

That disruption in traditional farming systems intensified as harvests of export crops such as coffee and cotton utilized entire families as laborers. Perhaps the most disruption to the complementary division of labor by gender occurred in those areas in Africa, Latin America, and parts of Asia where male labor was pulled into mining activities. Whereas in the seasonal plantation crops, men could return home for plowing and land clearing, when they worked in the mines they were often gone for years at a time, which left women in charge of those farming systems. Particularly, in parts of southern Africa, where strict rules regulated the movement of people across national boundaries, agriculture became an almost entirely female phenomenon.

Integration into a world economic system changed land use—from subsistence crops and those destined for domestic markets to export crops. In much of Latin America, for example, large areas of very good land had been given out as Spanish or Portuguese land grants and were farmed extensively with livestock, predominately cattle. Indigenous peoples and *mestizos* had use rights to land, on which they raised subsistence crops in exchange for the labor they provided to the *hacendado*.

B. Impacts on the Shift to Export Crops

Different areas of Latin America entered the export crop market at different times. For example, the islands of the Caribbean were settled by colonists from several nations primarily because of their prime conditions for sugar production. Those areas were almost always export oriented. As a result on those islands, particularly in the English-speaking Caribbean, women produce most of the food crops. Male labor is used for the harvest of the plantation crops, particularly sugarcane.

In other areas of Latin America, few export crops were planted until the era of land reform, beginning in the early 1960s. Most land reforms propagated during that period was intended to make land more productive, not redistribute land. Under the threat of expropriation, many large landowners shifted from extensive agricultural systems to more intensive ones, including soybeans, cotton, even more sugarcane—all crops aimed for foreign markets. As a result, local populations, who had farmed the land as part of their usufruct rights, were displaced. Many moved to the cities, whereas others moved to less-desirable highland areas where they found that the traditional practices that worked well on flat ground tended to erode badly hillside lands. Others moved to jungle and rain forest areas, with equally disastrous results.

In more marginalized hillside populations, men continued to provide labor for the export crops, although increasingly, as in places like Brazil, women have done so as well. In the new cropping systems that emerged in the fragile highland areas, there was a marked division between his crops and her crops. She raised vegetables and tree crops around the house, and he raised row crops and commercial tree crops further away from the household living area. There was also an increase in the division of labor in animal raising, varying by area. Traditionally men are in charge of large animals, which required a certain capital investment, and women maintain the production of small animals, using them for both household consumption and sale in times of economic stress.

C. Impacts of Alienation of Land

A third important trend that has affected the division of labor by gender worldwide has been the movement toward the alienation of land. In traditional agricultural communities, much land was controlled in common with village leaders assigning land use on a year by year basis. In this system, women had access to land through traditional use rights. As land became titled and later sold, it was almost always titled in the name of the man in the household rather than the man and woman. The new private plots in the reformed areas and in new colonization and transmigration areas favored men's crops. There was seldom land left for the women's gardens, which were often vital for household nutrition and even survival. Women's collective production efforts were eliminated entirely. Often the animals that women would pasture, such as small ruminants, also were not allocated land for grazing.

These three trends have tended to break down the role complementarity previously present in traditional agricultural systems. One can no longer assume what men will do or women will do in agriculture. A lot depends on the differential factor markets by gender. For example, if there is a place where male labor pays more, the men may migrate. On the other hand, if women will work for less, often large exporters will hire primarily women to do the field work. Thus, there have been enormous shifts and breakdowns in the subsistence-oriented family and community-based agricultural production system.

III. Current Characteristics of Women in Agriculture Worldwide

Not only has there been traditional divisions of labor by gender in agricultural production, which have varied enormously over time and space, there has also been enormous variation of income streams within households. Different members of farming households have different sources of income, and those sources of income have different uses depending on the gender. In pre-World War II American agriculture, women very often had the egg and butter money earned by raising chickens or milking the cows and marketing the product in local markets.

Women's production was used either to barter for other kinds of food the family needed, such as coffee or salt at the local store, or for cash when necessary for other family necessities. Very often such cash could be used for special items of household consumption or even savings for children's schooling. Male income would be more likely to be reinvested in the farm itself.

A. Income Streams by Gender

In developing countries we find a wide variation in the intrahousehold income streams. In some areas household income is pooled. In other areas, women lend their husbands money at interest. The sale or home use of different crops is decided by different members of the family.

Income that goes directly to women in agricultural households is more likely to be used for household necessities, particularly children's food, clothing, and schooling. Men's income is often used for a variety of male bonding activities, such as drinking, that may contribute to community solidarity but not to household well-being. As a result of these different income flows, increasing a farm family's income does not equally benefit all family members. The existence of patriarchy, that is to say, the dominance of the oldest male in the household, tends to mean unequal and sometimes arbitrary distribution of income within any particular household.

B. Resource Access by Gender

The impact of unequal access to resources combined with heavy work loads for all household members can be judged by looking at the sex ratio in rural farm areas. There are generally many more men than women, despite the overall tendency of women to outnumber men as adults. Women are more likely to leave farm areas, as they feel the hard work that they put in on a farm, particularly in livestock operations such as dairy, is not worth the limited return in cash and respect that they receive. Thus, the constraints to participation in agricultural production for many women in advanced industrial societies come from a relatively high labor demand, little chance of leisure, and little control over resources for production. Although figures for many developed countries show women as major landowners, this gives a distorted picture. Women who own land are very often widows who are simply owning land as placeholders for their sons, who take on the major decision making and control of the agricultural production practices.

IV. Technology and Women

Agricultural technology has been developed to make both labor and land produce more per unit. However, most of that technology has been channeled toward men. For example, when chicken production became highly technical and market oriented, the technology was brought by the extension service to the males of the family, and women lost their source of separate incomes, although they would often do the work. Access to the credit needed to expand the chicken production in the high-technology buildings with the other high-technology inputs were aimed at men. In addition, the technical assistance that came either from the agricultural extension service or, later, the poultry integrators (large multinational corporations who purchased the chickens), was also almost entirely aimed at males. And the milk check, the chicken check, or the egg check would be written in the name of the male head of household.

In the developing world as well, technological innovation has tended to disadvantage women compared to men. The fact that women's income streams were not recognized often meant that income moved from female hands to male hands as more official marketing channels were put into place, such as milk production in the *altiplano* of Bolivia. Further, the labor that women did that gave them their income streams, such as rice hulling in parts of Africa and Asia, was, when mechanized, taken over by men, leaving women without the hard work, but also without the important income that it generated.

A number of studies in different parts of the world have shown that farm women produce as much as farm men when they have access to similar resources. This includes education, access to markets, access to credit, and access to technical assistance. New inputs and marketing channels of agriculture are gendered, and they are biased almost always toward men and away from women.

V. Gendered Patterns of Production

Despite the gendering of the factor markets necessary for production, including land, labor, and capital markets, a number of different gender patterns in agriculture have emerged and are present in different areas and in different proportions. The first is separate, different agricultural enterprises. This occurs most often in Africa but also in parts of Latin America and the Caribbean, where men will have particular crops for particular markets and women will have quite different crops with quite different markets.

The second pattern is separate, similar agricultural enterprises. For example, both may raise vegetables. In the Caribbean, men may raise vegetables for a world market, whereas women may raise vegetables for the local market. The first pattern has implications for agricultural research and extension in that there is a tendency to focus only on the crops males raise. The second pattern has implications for agricultural research and extension in that, particularly in the fruits and vegetables, those for a local market can have different characteristics than those for markets where extensive shipping is required. Thus, they will use different varieties of the same species.

A third pattern involves separate tasks within the same enterprise. This often occurs in developed countries, as well as in developing countries, where men will be in charge of plowing, women in charge of seed selection, both do planting, both do harvesting, men do tilling, and women do postharvest processing.

A fourth pattern, much less common, is shared tasks in the same enterprise. Although such ungendered task sharing is occurring in Canada, the United States, and Europe, this pattern has actually decreased as increasing stress on farm incomes has forced men and women off the farm to seek outside income. Interestingly enough, in many rural areas, women have an advantage in terms of off-farm employment. Thus, men take over many of the jobs that they once shared with their wives.

The final pattern, which is increasing in many developing countries and in certain parts of the developed world, are female-run enterprises that are both the de facto (the enterprise has a male head of household but the women actually runs it because the male is gone for all or most of the year) and the de jure female-headed enterprises (the land and resources are legally in the woman's name). De jure female farms are much less common. They tend to be present in developed countries where there is an increasing number of women choosing to engage in agriculture on their own.

VI. Implications for Agricultural Change

The recognition of the role of women in agriculture, as landowners, agricultural managers, and agricultural workers, is extremely important in understanding how agriculture will change over time. For example, women agricultural workers are very prevalent in export crops production in many developing countries, especially in harvesting and immediate postharvest processing. Women tend to be used because they are a cheaper, more docile labor force than men for a variety of reasons due to segmentation of the labor market. In many developed countries, on the other hand, male migrant laborers serve the same function and may displace female local workers.

Agricultural research will be different if it recognizes the role of women. It may change the types of crops or animal enterprises that are researched, and it might change the characteristics that are bred for or the type of farming practices that are developed, depending on recognition of the differential needs of different types of producers.

Agricultural extension would change if there was recognition of the types of agricultural work that women actually do and the fact that "trickle across" does not work. If women carry out the tasks, then women need to be directly trained to do them.

Agricultural marketing would also change if there was an awareness of what women actually do in agriculture. For example, if women do the work, agricultural marketing that allows them to receive the cash for the product would lead to increased and more efficient production. Utilizing women's groups for marketing or including women in existing agricultural marketing cooperatives as a specific policy might be very important in a number of situations.

In value-added agriculture, understanding who does what when can be extremely important. Value-added practices, such as cheesemaking in a number of areas, often takes away from what women traditionally did to earn income by mechanizing the process and turning it over to men. On the other hand, a number of artisanry or rustic development projects which have women use very traditional means to process food after it is produced may add to women's work, but not to their incomes. Thus, value-added strategies must include awareness of not only who does what, but who has control over which resources in agricultural production.

Finally, recognizing the role of women in agriculture has enormous implications for how agricultural communities are organized. It is important to recognize women's role as wage laborers and their need for the kinds of services that facilitate their participation in the labor force, such as health care and child care as well as organizing agricultural communities, particularly regarding natural resource management. It is very important to include women in natural resource management, as they often have particular interests in common property as well as in individual property.

VII. Sustainable Agriculture and Women

Sustainable agriculture contributes to the survival of farm families on the land, maintains and improves environmental quality, and maintains and improves agricultural communities and the quality of life for individuals in them, as well as in urban areas. Agriculture, as part of many watersheds, is also important for maintaining a safe water supply, as well as a safe food supply.

Sustainable agriculture often uses a wide variety of new technologies in new ways. To be successful, it must be aware of the gendered division of labor, as well as control over resources by gender. Sustainable agriculture demands a community commitment as well as an individual commitment toward social change. Local knowledge of both men and women is important in developing a more sustainable agriculture. Women's knowledge of biodiversity as well as practices that sustain the soil and maintain the water supply will be crucial in this. [*See* SUSTAINABLE AGRICULTURE.]

Ecofeminism states that women have a particular concern and linkage to the soil and animals and, thus, an inbred desire to sustain and protect them. Those who are antiessentialists in viewing women and the land point out that there are cultural reasons why women would be more concerned about sustainable agriculture than would men, who often have a shorter time frame in seeking profits. Certainly, we can attribute much of the degradation of land to male agricultural practices, such as the suitcase farming that went on in the western United States that helped set up the dust bowl. But this may be because men had control over the land, not because men are inherently less sustainability oriented than women.

VIII. Conclusions

Women have been, and continue to be, active in agriculture as workers, owners, and managers of both common agricultural land and individually held agricultural resources. Understanding the specificity of women's activities can help make agriculture more efficient and effective as resources are developed and targeted to the part of the population that can best use it. But because gender is a social phenomenon, it must be understood in context. There is little we can generalize about women in agriculture worldwide, except that it is important to take what they do into account.

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Wood Properties

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Glossary

Allowable property Value of a property normally published for design use; allowable properties are identified with grade descriptions and standards, and they reflect the orthotropic structure of wood and anticipated end uses

Anisotropic Exhibiting different properties along different axes; in general, fibrous materials such as wood are anisotropic

Annual growth ring Layer of wood growth put on a tree during a single growing season. In the temperate zone, the annual growth rings of many species (e.g., oaks and pines) are readily distinguished because of differences in the cells formed during the early and late parts of the season; in some temperate zone species (e.g., black gum and sweetgum) and many tropical species, annual growth rings are not easily recognized

Diffuse-porous wood Certain hardwoods in which the pores tend to be uniformly sized and distributed throughout each annual ring or to decrease in size slightly and gradually toward the outer border of the ring

Earlywood Portion of the annual growth ring that is formed during the early part of the growing season; it is usually less dense and mechanically weaker than latewood

Hardwoods General botanical group of trees that has broad leaves in contrast to the conifers or softwoods; term has no reference to the actual hardness of the wood

Latewood Portion of the annual growth ring that is formed after the earlywood formation has ceased; it is usually denser and mechanically stronger than earlywood

Lumber Product of the saw and planing mill manufactured from a log through the process of sawing, resawing to width, passing lengthwise through a standard planing machine, and crosscutting to length

Orthotropic Having unique and independent properties in three mutually orthogonal (perpendicular) planes of symmetry; a special case of anisotropy

Ring-porous woods Group of hardwoods in which the pores are comparatively large at the beginning of each annual ring and decrease in size more or less abruptly toward the outer portion of the ring, thus forming a distinct inner zone of pores, the earlywood, and an outer zone with smaller pores, the latewood

Softwoods General botanical group of trees that in most cases has needlelike or scalelike leaves (the conifers); term has no reference to the actual hardness of the wood

Wood is an extremely versatile material with a wide range of physical and mechanical properties among the many species of wood. It is also a renewable resource with an exceptional strength-to-weight ratio. Wood is a desirable construction material because the energy requirements of wood for producing a usable end-product are much lower than those of competitive materials, such as steel, concrete, or plastic.

I. Wood Structure

A. Microstructure

The primary structural building block of wood is the tracheid or fiber cell. Cells vary from 16 to 42 μm in

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diameter and from 870 to 4000 μm long. Thus, a cubic centimeter of wood could contain more than 1.5 million wood cells. When packed together they form a strong composite. Each individual wood cell is even more structurally advanced because it is actually a multilayered, filament-reinforced, closed-end tube (Fig. 1) rather than just a homogeneous-walled, nonreinforced straw. Each individual cell has four distinct cell wall layers (Primary, S_1, S_2, and S_3). Each layer is composed of a combination of three chemical polymers: cellulose, hemicellulose, and lignin (Fig. 1). The cellulose and hemicellulose are linear polysaccharides (i.e., hydrophilic multiple-sugars), and the lignin is an amorphous phenolic (i.e., a three-dimensional hydrophobic adhesive). Cellulose forms long unbranched chains, and hemicellulose forms short branched chains. Lignin encrusts and stiffens these polymers.

Because carbohydrate and phenolic components of wood are assembled in a layered tubular or cellular manner with a large cell cavity, specific gravity of wood can vary immensely. Wood excels as a viable building material because the layered tubular structure provides a large volume of voids (void volume), it has an advantageous strength-to-weight ratio, and it has other inherent advantages, such as corrosion resistance, fatigue resistance, low cost, and ease-of-modification at the job site.

B. Macrostructure

The cross-section of a tree is divided into three broad categories consisting of the bark, wood, and cambium (Fig. 2). Bark is the outer layer and is composed of a dead outer phloem of dry corky material and a thin inner phloem of living cells. Its primary functions are protection and nutrient conduction. The thickness and appearance of bark vary substantially depending on the species and age of the tree.

Wood, or xylem, is composed of the inner sections of the trunk. The primary functions of wood are support and nutrient conduction and storage. Wood can be divided into two general classes: sapwood and heartwood. Sapwood is located next to the cambium. It functions primarily in food storage and the mechanical transport of sap. The radial thickness of sapwood is commonly 35 to 50 mm but may be 75 to 150 mm for some species. Heartwood consists of an inner core of wood cells that have changed, both chemically and physically, from the cells of the outer sapwood. The cell cavities of heartwood may also contain deposits of various materials that frequently give heartwood a much darker color. Extractive deposits formed during the conversion of living sapwood to dead heartwood often make the heartwood of some species more durable in conditions that may induce decay.

The cambium is a continuous ring of reproductive tissue located between the sapwood and the inner layer of the bark. Usually, it is 1 to 10 cells wide depending on the season. All wood and bark cells are aligned or stacked radially because each cell in a radial line originated from the same cambial cell.

1. Growth

Growth in trees is affected by the soil and environmental conditions with which the tree must exist and

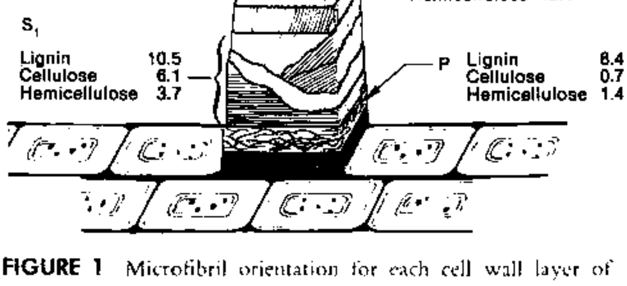

FIGURE 1 Microfibril orientation for each cell wall layer of Scotch pine with chemical composition as percentage of total weight. Cell wall layers are primary (P), S_1, S_2, and S_3.

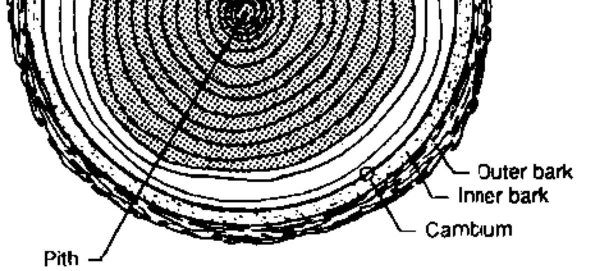

FIGURE 2 Elements of macrostructure normally visible without magnification.

contend. Growth is accomplished by cell division. As new cells form, they are pushed either to the inside to become wood cells or to the outside to become bark cells. As the diameter of the tree increases, new cells are also occasionally retained in the cambium to account for increasing cambial circumference. Also, as the tree diameter increases, additional bark cells are pushed outward, and the outer surface becomes cracked and ridged, forming the bark patterns characteristic of each species.

The type and rate of growth vary between earlywood and latewood cells. Earlywood cells have relatively large cavities and thin walls, whereas latewood cells have smaller cavities and thicker walls. Because void volume is related to density and density is related to lumber strength, latewood is sometimes used to judge the quality or strength of some species. Earlywood is lighter in weight and color, softer, and weaker than latewood; it shrinks less across the grain and more lengthwise along the grain than does latewood.

2. Growth Rings

Growth rings vary in width depending on species and site conditions. Rings formed during short or dry seasons are thinner than those formed when growing conditions are more favorable. Also, rings formed in shady conditions are usually thinner than those formed by the same species in sunny conditions. It is commonly believed that the age of a tree may be determined by counting these rings. However, this method can lead to errors because abnormal environmental conditions can cause a tree to produce multiple-growth increments or even prevent growth entirely for a period.

3. Knots

As a tree grows, branches develop laterally from the trunk. These branches produce gross deviations in the normal grain of the trunk and result in knots when the log is sawn into lumber or timber. Knots are classified in two categories: intergrown knots and encased or loose knots. Intergrown knots are formed by living branches. Encased knots occur when branches die and the wound is surrounded by the growing trunk. Knots result in grain deviations, which is significant because straight-grained wood is approximately 10 to 20 times stronger parallel to grain than perpendicular to grain. Accordingly, knot size is a major predictor of sawn-timber strength.

4. Reaction Wood

Reaction wood is the response of a tree to abnormal environmental or physical stresses associated with leaning trees and crooked limbs. It is generally believed to be an attempt by the tree to return the trunk or limbs to a more natural position. In softwoods, reaction wood is called compression wood and results in the production of wood cells rich in phenolic lignin and poor in carbohydrates. It is found on the lower side of the limb or inclined trunk and effectively results in a higher cell wall packing density and high compression strength. Many of the anatomical, chemical, physical, and mechanical properties of reaction wood differ distinctly from those of normal wood. The specific gravity of compression wood is frequently 30 to 40% greater than that of normal wood, but the tensile strength is many times lower. This is why all grading rules restrict compression wood in any form from graded softwood lumber and timber.

II. Physical Properties

Physical properties are the quantitative characteristics of wood and its behavior to external influences other than applied forces. Included here are directional properties, moisture content, dimensional stability, thermal and pyrolytic (fire) properties, density, and electrical, chemical, and decay resistance. Familiarity with physical properties is important because they can significantly influence the performance and strength of wood used in structural applications.

The physical properties of wood most relevant to structural design and performance are discussed in this section. The effects that variations in these properties have on the strength of wood are more fully discussed in Section IV.

A. Directional Properties

Wood is an orthotropic and anisotropic material. Because of the orientation of the wood fibers and the manner in which a tree increases in diameter as it grows, properties vary along three mutually perpendicular axes: longitudinal, radial, and tangential (Fig. 3). The longitudinal axis is parallel to the fiber (grain) direction, the radial axis is perpendicular to the grain direction and normal to the growth rings, and the tangential axis is perpendicular to the grain direction and tangent to the growth rings. Although most wood properties differ in each of these three axis directions, differences between the radial and tangential axes are relatively minor when compared to differences between the radial or tangential axis and the

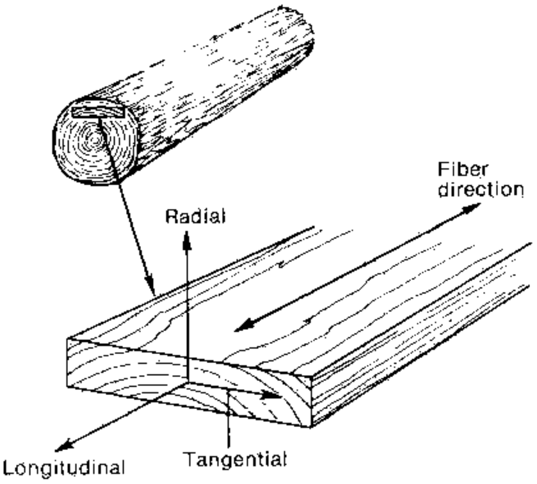

FIGURE 3 Three principal axes of wood with respect to grain direction and growth rings.

longitudinal axis. Property values tabulated for structural applications are often given only for axis directions parallel to grain (longitudinal) and perpendicular to grain (radial or tangential).

B. Moisture Content

The moisture content of wood is defined as the weight of water in wood given as a percentage of ovendry weight. In equation form, moisture content (MC) is expressed as follows:

$$\mathrm{MC} = \frac{\text{moist weight} - \text{dry weight}}{\text{dry weight}} \times 100\%. \quad (1)$$

Water is required for the growth and development of living trees and constitutes a major portion of green wood anatomy. In living trees, moisture content depends on the species and the type of wood, and may range from approximately 25% to more than 250% (two and a half times the weight of the dry wood material). In most species, the moisture content of sapwood is higher than that of heartwood.

Water exists in wood either as bound water (in the cell wall) or free water (in the cell cavity). As bound water, it is bonded (via secondary or hydrogen bonds) within the wood cell walls. As free water, it is simply present in the cell cavities. When wood dries, most free water separates at a faster rate than bound water because of accessibility and the absence of secondary bonding. The moisture content at which the cell walls are still saturated but virtually no water exists in the cell cavities is called the fiber saturation point. The fiber saturation point usually varies between 21 and 28%.

Wood is a hygroscopic material that absorbs moisture in a humid environment and loses moisture in a dry environment. As a result, the moisture content of wood is a function of atmospheric conditions and depends on the relative humidity and temperature of the surrounding air. Under constant conditions of temperature and humidity, wood reaches an equilibrium moisture content (EMC) at which it is neither gaining nor losing moisture. The EMC represents a balance point where the wood is in equilibrium with its environment.

In structural applications, the moisture content of wood is almost always undergoing some changes as temperature and humidity conditions vary. These changes are usually gradual and short-term fluctuations that influence only the surface of the wood. The time required for wood to reach the EMC depends on the size and permeability of the member, the temperature, and the difference between the moisture content of the member and the EMC potential of that environment. Changes in moisture content cannot be entirely stopped but can be retarded by coatings or treatments applied to the wood surface.

C. Dimensional Stability

Above the fiber saturation point, wood will not shrink or swell from changes in moisture content because free water is found only in the cell cavity and is not associated within the cell walls. However, wood changes in dimension as moisture content varies below the fiber saturation point. Wood shrinks as it loses moisture below the fiber saturation point and swells as it gains moisture up to the fiber saturation point. These dimensional changes may result in splitting, checking, and warping. The phenomena of dimensional stability and EMC must be understood, recognized, and considered in good timber design.

Dimensional stability of wood is one of the few properties that significantly differs in each of the three axis directions. Dimensional changes in the longitudinal direction between the fiber saturation point and ovendry are between 0.1 and 0.2% and are of no practical significance; however, in reaction or juvenile wood, these percentages may be significantly higher. The combined effects of shrinkage in the tangential and radial axes can distort the shape of wood pieces because of the difference in shrinkage and the curvature of the annual rings (Fig. 4). Generally, tangential shrinkage (varying from 4.4 to 7.8% depending on species) is twice that of radial shrinkage (from 2.2 to 5.6%).

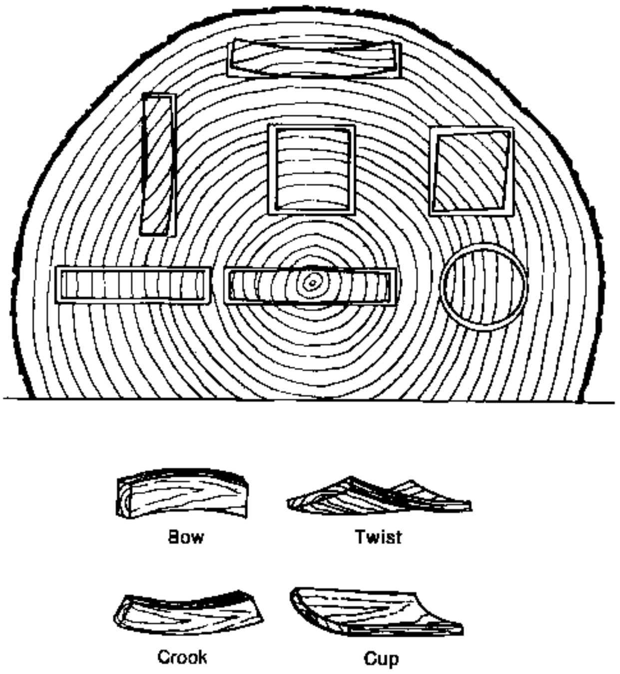

FIGURE 4 Characteristic shrinkage and distortion of wood as affected by direction of growth rings. Such distortion can result in warp, generally classified as bow, twist, crook, and cup.

D. Thermal Expansion

Thermal expansion of dry wood is positive in all directions; wood expands when heated and contracts when cooled. Wood that contains moisture reacts to temperature changes differently than dry wood.

The linear expansion coefficients of dry wood parallel to grain are generally independent of specific gravity and species and range from approximately 3×10^{-6} to 4.5×10^{-6} per °C. The linear expansion coefficients across the grain (tangential and radial) are in proportion to density and range from approximately 5 to 10 times greater than parallel to grain coefficients.

When moist wood is heated, it tends to expand because of normal thermal expansion and shrink because of moisture loss from increased temperature. Unless the initial moisture content of the wood is very low (3 to 4%), the net dimensional change on heating is negative. Wood at intermediate moisture contents of approximately 8 to 20% will expand when first heated, then gradually shrink to a volume smaller than the initial volume as moisture is lost in the heated condition.

E. Pyrolytic Properties

Under appropriate conditions, wood will undergo thermal degradation or pyrolysis. The by-products of pyrolysis may burn, and if enough heat is generated and retained by the wood, the wood can be set on fire. In the presence of a pilot flame (independent source of ignition), the minimum rate of heating necessary for ignition is of the order of 0.3 calorie per square centimeter. In the absence of a pilot flame, the minimum rate of heating necessary for ignition is of the order of 0.6 calorie per square centimeter, nearly double the rate of the pilot flame situation.

Still, heavy timber construction deserves an extremely favorable fire-insurance rating because it will generally not produce sufficient heat energy to maintain combustion unless an external heat source is present. Timber will gradually produce a char layer from the residue of wood combustion. This char acts as a thermal insulator. On heavy timbers, this char layer will eventually inhibit combustion by establishing a thermal barrier between the uncharred wood (interior to char) and the heat of the fire (exterior to char). Heavy timber is virtually self-extinguishing, but steel, which has a thermal conductivity 100 times that of wood, will absorb heat until it reaches a temperature at which it yields under structural load without actually burning.

F. Density and Specific Gravity

The density of a material is the mass per unit volume at some specified condition. For a hygroscopic material such as wood, density depends on two factors: the weight of the wood structure and moisture retained in the wood. Wood density at various moisture contents can vary significantly and must be given relative to a specific condition to have practical meaning.

Specific gravity provides a relative measure of the amount of wood substance contained in a sample of wood. It is a dimensionless ratio of the weight of an ovendry volume of wood to the weight of an identical volume of water. In research activities, specific gravity may be reported on the basis of both weight and volume ovendry. For many engineering applications, the basis for specific gravity is generally the ovendry weight and volume at a moisture content of 12%. For example, a volume of wood at some specified moisture content with a specific gravity of 0.50 would have a density of 500 kg/m^3.

G. Electrical Resistance

Wood is a good electrical insulator. However, significant variations in conductivity do exist. These variations in electrical resistance can be related to variations in grain orientation, temperature, and moisture content. The conductivity of wood in the longitudinal axis is approximately twice that in the radial or tangential axes. The electrical conductivity of wood generally doubles for each 10°C increase in temperature. Generally, variations in conductivity related to wood density and species are considered minor.

The correlation between electrical resistivity and moisture content is the basis for electrical resistance-type moisture meters that estimate moisture content by measuring the resistance of the wood between two electrodes. Moisture content meters, as these instruments are commonly called, need to be calibrated for temperature and species and are effective only for moisture content ranges of 5 to 25%. They are generally unreliable for high resistivities at moisture contents below 5 or 6%, for estimating the moisture content of green timber, or for estimating moisture content of treated timbers (most treatments alter conductivity).

H. Decay Resistance

Wood decay fungi and wood-destroying organisms require oxygen, appropriate temperature, moisture, and a food source. Wood will not decay if kept dry (moisture content less than 20%). On the other extreme, if continuously submerged in water at sufficient depths, wood will usually not decay. Whenever wood is intermediary to either of these two extremes, problems with wood decay can result. To avoid problems with decay where moisture cannot be controlled, the engineer or designer can use either naturally durable species or treated timber.

The natural durability of wood to the mechanisms and processes of deterioration is related to the anatomical characteristics and species of wood. In general, the outer zone or sapwood of all species has little resistance to deterioration and fails rapidly in adverse environments. For heartwood, natural durability depends on species. Heartwood forms as the living sapwood cells gradually die. In some species, the sugars present in the cells are converted to highly toxic extractives that are deposited in the wood cell wall. Many species produce durable heartwood, including western red cedar, redwood, and black locust; however, durability varies within a tree and between trees of a given species. To enhance durability, wood can be treated with an EPA-registered, toxic preservative chemical treatment.

I. Chemical Resistance

Wood is highly resistant to many chemicals, which gives it a significant advantage over many alternative building materials. Wood is often considered superior to alternative materials, such as concrete and steel, partly because of its resistance to mild acids (pH more than 2.0), acidic salt solutions, and corrosive agents. Generally, iron holds up better on exposure to alkaline solution than does wood, but wood can be treated with many of the common wood preservatives (e.g., creosote) to greatly enhance its performance in this respect.

Heartwood is far more durable than sapwood to chemical attack because heartwood is more resistant to penetration by liquids. Many preservative treatments, such as creosote or pentachlorophenol in heavy oil, can also significantly increase the ability of wood to resist liquid or chemical penetration, or both. Chemical solutions may induce two general types of action: normal reversible swelling by a liquid and irreversible chemical degradation. With the former, removal of the liquid will return wood to its original condition. With the latter, permanent changes occur within the wood structure from hydrolysis, oxidation, or delignification.

III. Mechanical Properties

Mechanical properties are the characteristics of a material in response to externally applied forces. They include elastic properties, which characterize resistance to deformation and distortion, and strength properties, which characterize resistance to applied loads. Mechanical property values are given in terms of stress (force per unit area) and strain (deformation resulting from the applied stress). The mechanical property values of wood are obtained from laboratory tests of lumber of straight-grained clear wood samples (without natural defects that would reduce strength, such as knots, checks, splits, etc.).

A. Elastic Properties

Elastic properties relate the resistance of a material to deformation under an applied stress to the ability of the material to regain its original dimensions when the stress is removed. For a material with ideal elastic properties loaded below the proportional (elastic) limit, all deformation is recoverable and the body returns to its original shape when the stress is removed. Wood is not ideally elastic in that some deformation from loading is not immediately recovered when the load is removed; however, residual deformations are generally recoverable over a period of time. Although technically considered a viscoelastic material, wood is usually assumed to behave as an elastic material for most engineering applications.

For an isotropic material with equal property values in all directions, elastic properties are measured by three elastic constants: modulus of elasticity (E), modulus of rigidity (G), and Poisson's ratio (μ). The following equation shows the relationship:

$$\mu_{ij} = E_k/G_{ij}, \tag{2}$$

where i, j, and k represent the three principal axes. Because wood is orthotropic, 12 constants are required to measure elastic behavior: three moduli of elasticity, three moduli of rigidity, and six Poisson's ratios.

1. Modulus of Elasticity

Modulus of elasticity relates the stress applied along one axis to the strain occurring on the same axis. The three moduli of elasticity for wood are denoted E_L, E_R, and E_T to reflect the elastic moduli in the longitudinal, radial, and tangential directions, respectively. For example, E_L relates the stress in the longitudinal direction to the strain in the longitudinal direction.

Elastic constants vary within and between species and with moisture content and specific gravity. The only constant that has been extensively derived from test data is E_L. Other constants may be available from limited test data but are most frequently developed from material relationships or by regression equations that predict behavior as a function of density. Relative values of elastic constants for clearwood of several common wood species are given in Table I.

2. Shear Modulus

Shear modulus relates shear stress to shear strain. The three shear moduli for wood are denoted G_{LR}, G_{LT}, and G_{RT} for the longitudinal-radial, longitudinal-tangential, and radial-tangential planes, respectively. For example, G_{LR} is the modulus of rigidity based on the shear strain in the LR plane and the shear stress in the LT and RT planes. The modulus of rigidity for several wood species and for each plane are given in Table I.

3. Poisson's Ratio

Poisson's ratio relates the strain parallel to an applied stress to the accompanying strain occurring laterally. For wood, the six Poisson's ratios are denoted μ_{LR}, μ_{LT}, μ_{RL}, μ_{RT}, μ_{TL}, and μ_{TR}. The first subscript refers to the direction of applied stress; the second subscript refers to the direction of the accompanying lateral strain. For example, μ_{LR} is the Poisson's ratio for stress along the longitudinal axis and strain along the radial axis. Estimates of Poisson's ratios for several wood species and for each orientation are given in Table I.

B. Strength Properties

Strength properties are the ultimate resistance of a material to applied loads. With wood, strength varies significantly depending on species, loading condition, load duration, and a number of assorted material and environmental factors.

Because wood is anisotropic, mechanical properties also vary in the three principal axes. Property values in the longitudinal axis are generally significantly higher than those in the tangential or radial axes. Strength-related properties in the longitudinal axis are usually referred to as parallel-to-grain properties. For most engineering design purposes, simply differentiating between parallel- and perpendicular-to-grain properties is sufficient because the relative tangential and radial directions are randomized by the primary sawing process (i.e., conversion from logs to boards).

1. Compression

When a compression load is applied parallel to grain, it produces stress that deforms (shortens) wood cells along their longitudinal axis. When wood is stressed in compression parallel to grain, failure initially begins as the microfibrils begin to fold within the cell wall, thereby creating planes of weakness or instability within the cell wall. As stress in compression parallel to grain continues to increase, the woodcells themselves fold into S shapes, forming visible wrinkles on the surface. Large deformations occur from the internal crushing of the complex cellular structure. The average strength of green clear wood specimens of Douglas-fir and loblolly pine in compression parallel to grain is approximately 26.1 and 24.2 MPa, respectively.

When a compression load is applied perpendicular to grain, it produces stress that deforms the wood cells perpendicular to their length. Once the hollow cell cavities are collapsed, wood is quite strong because no void space exists. In practice, compressive strength of wood perpendicular to grain is usually assumed to be exceeded when deformation exceeds 4% of the proportional limit stress. Using this convention, the average strength of green clear wood specimens of Douglas-fir and loblolly pine in compression perpendicular to grain is approximately 4.8 and 4.6 MPa, respectively.

Compression applied at an angle to the grain produces stresses that act both parallel and perpendicular

TABLE I

Elastic Ratios for Various Species

Species	Approximate specific gravity[a]	Approximate moisture content (percentage)	Modulus of elasticity ratio[b]		Ratio of modulus of rigidity to modulus of elasticity[c]			Poisson's ratio[d]					
			E_T/E_L	E_R/E_L	G_{LR}/E_L	G_{LT}/E_L	G_{RT}/E_L	μ_{LR}	μ_{LT}	μ_{RT}	μ_{TR}	μ_{RL}	μ_{TL}
Balsa	0.13	9	0.015	0.046	0.054	0.037	0.005	0.23	0.49	0.67	0.23	0.02	0.01
Birch, yellow	0.64	13	0.050	0.078	0.074	0.068	0.017	0.43	0.45	0.70	0.43	0.04	0.02
Douglas-fir	0.50	12	0.050	0.068	0.064	0.078	0.007	0.29	0.45	0.39	0.37	0.04	0.03
Spruce, Sitka	0.38	12	0.043	0.078	0.064	0.061	0.003	0.37	0.47	0.44	0.24	0.04	0.02
Sweetgum	0.53	11	0.050	0.115	0.089	0.061	0.021	0.32	0.40	0.68	0.31	0.04	0.02
Walnut, black	0.59	11	0.056	0.106	0.085	0.062	0.021	0.50	0.63	0.72	0.38	0.05	0.04
Yellow-poplar	0.38	11	0.043	0.092	0.075	0.069	0.011	0.32	0.39	0.70	0.33	0.03	0.02

[a] Based on ovendry weight and volume at the moisture content shown.

[b] E is modulus of elasticity; T, tangential axis, L, longitudinal axis, R, radial axis.

[c] G is modulus of ridigity.

[d] μ is Poisson's ratio.

to grain. The strength at any intermediate angle is intermediate to values of compression parallel and perpendicular to grain and is determined using Hankinson's formula.

2. Tension

Parallel to its grain, wood is very strong in tension. Failure occurs by a complex combination of two modes: cell-to-cell slippage and cell wall failure. Slippage occurs where two adjacent cells slide past one another. Cell wall failure involves rupture within the cell wall with little or no visible deformation prior to complete failure. Tensile strength parallel to grain for clear wood has been historically difficult to obtain; it is often conservatively estimated from bending test values because clear wood normally exhibits initial failure on the face stressed in tension.

In contrast to tension parallel to grain, wood is relatively weak when loaded in tension perpendicular to grain. Stresses in this direction act perpendicular to the cell lengths and produce splitting or cleavage along the grain, which can have a significant effect on structural integrity. Deformations are usually low prior to failure because of the geometry and structure of the cell wall cross-section. Strength in tension perpendicular to grain for clear green samples of Douglas-fir and loblolly pine average 2.1 and 1.8 MPa, respectively. However, because of the excessive variability associated with ultimate stress in tension perpendicular to grain, design situations that induce this stress should be avoided.

3. Bending

Flexural (bending) properties are critical. Bending stresses are induced when a material is used as a beam, such as in a floor or rafter system. The bending strength of clear Douglas-fir and loblolly pine averages 52.6 and 50.3 MPa, respectively, while the modulus of elasticity averages 10.7 and 9.7 GPa, respectively. Because tensile and compressive strengths parallel to grain are different from each other, the strength in bending is less than in tension but more than in compression.

4. Shear

When used as a beam, wood is exposed to compression stress on one surface of the beam and tensile stress on the other. This opposition of stress results in a shearing action through the section of the beam. This parallel-to-grain shearing action is termed horizontal shear. The horizontal shear strength of clear Douglas-fir and loblolly pine averages 6.2 and 5.9 MPa, respectively. Conversely, when stress is applied perpendicular to the cell length in a plane parallel to grain, this action is termed rolling shear. Rolling shear stresses produce a tendency for the wood cells to roll over one another. In general, rolling shear strength values for clear specimens average 18 to 28% of the parallel-to-grain shear values.

5. Energy Absorption Resistance

Energy absorption or shock resistance is a function of the ability of a material to quickly absorb and then dissipate energy via deformation. Wood is remarkably resilient in this respect and is often a preferred material for shock loading. Several parameters are used to describe energy absorption depending on the eventual criteria of failure considered. Work to proportional limit, work to maximum load, and work to total failure (i.e., toughness) describe the energy absorption of wood materials at progressively more severe failure criteria.

6. Fatigue

The fatigue resistance of wood is sometimes an important consideration. Wood, like many fibrous materials, is quite resistant to fatigue (i.e., the effects of repeated loading). In many crystalline metals, repeated loadings of 1 to 10 million cycles at stress levels of 10 to 15% of ultimate can induce fatigue-type failures. At comparable stress levels, the fatigue strength of wood is often several times that of most metals.

7. Hardness

Hardness represents the resistance of wood to indentation and marring. Hardness is comparatively measured by force required to embed a 11.3-mm ball one-half its diameter into the wood.

IV. Factors Affecting Properties of Wood

To this point, our discussions of wood properties have mostly been based on tests of straight-grained specimens of clear wood. Clear wood properties are important, but by no means do they totally represent the engineering performance of solid-sawn lumber, timber, or glulam (glued-laminated timber) containing knots, slope of grain, and other strength-reducing characteristics. To understand the properties of these end-use products, the user must appreciate

TABLE II

Mechanical Properties of Some Commercially Important Woods Grown in the United States[a]

Common name of species	Moisture condition	Specific gravity[b]	Static bending			Impact bending[d] (m)	Compression parallel to grain[e] (MPa)	Compression perpendicular to grain[f] (MPa)	Shear parallel to grain[g] (MPa)	Tension perpendicular to grain[h] (MPa)	Side hardness-load perpendicular to grain (kN)
			Modulus of rupture (MPa)	Modulus of elasticity[c] (GPa)	Work to maximum load (kJ/m³)						
						Hardwoods					
Ash,	Green	0.35	34.9	5.89	43.8	0.56	14.7	1.2	4.5	1.6	1.33
quaking	Dry	0.38	57.5	8.08	52.0	0.53	29.1	2.5	5.8	1.8	1.56
Cherry,	Green	0.47	54.8	8.97	87.6	0.84	24.2	2.5	7.7	3.9	2.94
black	Dry	0.50	84.2	10.20	78.1	0.74	48.7	4.7	11.6	3.8	4.23
Cottonwood,	Green	0.37	36.3	6.92	50.0	0.53	15.6	1.4	4.7	2.8	1.51
eastern	Dry	0.40	58.2	9.38	50.7	0.51	33.6	2.6	6.4	4.0	1.91
Elm,	Green	0.46	49.3	7.60	80.8	0.97	19.9	2.5	6.8	4.0	2.76
American	Dry	0.50	80.8	9.18	89.0	0.99	37.8	4.7	10.3	4.5	3.69
Hickory,	Green	0.64	75.3	10.75	162.3	1.88	31.4	5.8	11.4		
shagbark	Dry	0.72	138.3	14.79	176.7	1.70	63.1	12.1	16.6	—	—
Maple											
Red	Green	0.49	52.7	9.52	78.3	0.81	22.5	2.7	7.9	—	3.11
	Dry	0.54	91.8	11.23	85.6	0.81	44.8	6.8	12.7	—	4.23
Sugar	Green	0.56	64.4	10.61	91.1	1.02	27.5	4.4	10.1	—	4.31
	Dry	0.63	108.2	12.53	113.0	0.99	53.6	10.1	16.1	—	6.45
Oak											
Northern	Green	0.56	56.8	9.24	90.4	1.12	23.6	4.2	8.3	5.1	4.45
red	Dry	0.63	97.9	12.46	99.3	1.09	46.3	6.9	12.2	5.5	5.74
White	Green	0.60	56.8	8.36	79.4	1.07	24.4	4.6	8.6	5.3	4.72
	Dry	0.68	104.1	12.19	101.3	0.94	[illegible]	7.3	13.7	5.5	6.05
Walnut,	Green	0.51	65.1	9.72	100.0	0.94	29.4	3.4	8.4	3.9	4.00
black	Dry	0.55	100.0	11.59	73.3	0.86	52.3	6.9	9.4	4.7	4.49
Yellow-	Green	0.40	41.1	8.35	51.4	0.66	18.3	1.8	5.4	3.5	1.96
poplar	Dry	0.42	69.2	10.82	60.3	0.61	37.9	3.4	8.1	3.7	2.40
						Softwoods					
Cedar,	Green	0.31	35.6	6.44	34.2	0.43	19.6	1.6	5.3	1.6	1.16
western red	Dry	0.32	51.4	7.60	39.7	0.43	31.2	3.1	6.8	1.5	1.56
Douglas-fir,	Green	0.45	52.7	10.68	52.0	0.66	25.9	2.6	6.2	2.1	2.22
coast	Dry	0.48	84.9	13.35	67.8	0.79	49.5	5.5	7.7	2.3	3.16

Fir											
Balsam	Green	0.33	37.7	8.56	32.2	0.41	18.0	1.3	4.5	1.2	1.29
	Dry	0.35	63.0	9.93	34.9	0.51	36.2	2.8	6.5	1.2	1.78
White	Green	0.37	40.4	7.94	38.3	0.56	19.9	1.9	5.2	2.1	1.51
	Dry	0.39	67.1	10.27	49.3	0.51	39.7	3.6	7.5	2.1	2.14
Hemlock,	Green	0.42	45.2	8.97	47.2	0.56	23.0	1.9	5.9	2.0	1.82
western	Dry	0.45	77.4	11.16	56.8	0.58	49.3	3.8	8.8	2.3	2.40
Larch,	Green	0.48	52.7	10.00	70.5	0.74	25.7	2.7	6.0	2.3	2.27
western	Dry	0.52	89.0	12.80	86.3	0.89	52.2	6.4	9.3	2.9	3.69
Pine											
Eastern	Green	0.34	33.6	6.78	35.6	0.43	16.7	1.5	4.7	1.7	1.29
white	Dry	0.35	58.9	8.49	46.6	0.46	32.9	3.0	6.2	2.1	1.69
Loblolly	Green	0.47	50.0	9.59	56.2	0.76	24.0	2.7	5.9	1.8	2.00
	Dry	0.51	87.6	12.26	71.2	0.76	48.8	5.4	9.5	3.2	3.07
Ponderosa	Green	0.38	34.9	6.85	35.6	0.53	16.8	1.9	4.8	2.1	1.42
	Dry	0.40	64.4	8.83	48.6	0.48	36.4	4.0	7.7	2.9	2.05
Redwood											
Old-growth	Green	0.38	51.4	8.08	50.7	0.53	28.8	2.9	5.5	1.8	1.82
	Dry	0.40	68.5	9.18	47.2	0.48	42.1	4.8	6.4	1.6	2.14
Young-growth	Green	0.34	40.4	6.57	39.0	0.41	21.3	1.8	6.1	2.1	1.56
	Dry	0.35	54.1	7.53	35.6	0.38	35.6	3.6	7.6	1.7	1.87
Spruce											
Sitka	Green	0.37	39.0	8.42	43.1	0.61	18.3	1.9	5.2	1.7	1.56
	Dry	0.40	69.8	10.75	64.4	0.64	38.4	4.0	7.9	2.5	2.27
White	Green	0.33	34.2	7.81	41.1	0.56	16.1	1.4	4.4	1.5	1.42
	Dry	0.36	64.4	9.79	52.7	0.51	35.5	2.9	6.6	2.5	2.14

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[a] Results of tests on small, clear, straight-grained specimens. Values in the first line for each species are from tests of green material; those in the second line are from tests of seasoned material adjusted to a 12% moisture content.

[b] Based on weight ovendry and volume at moisture content indicated.

[c] Measured from a simply supported, center-loaded beam, on a span-depth ratio of 14/1. The modulus can be corrected for the effect of shear deflection by increasing it 10%.

[d] Height of drop causing complete failure.

[e] Maximum crushing strength.

[f] Fiber stress at proportional limit.

[g] Maximum shearing strength.

[h] Maximum tensile strength.

[i] Douglas-fir in the States of Oregon and Washington west of the summit of the Cascade Mountains.

the impacts of several anatomical and processing-related factors. The user must also appreciate the interactive nature of environmental factors. This section will attempt to briefly relate the importance of many of these factors independently and in aggregate.

A. Anatomical Factors

The mechanical properties of wood vary between species; they are often compared via species averages (Table II). However, because mechanical properties vary within a species, it is incorrect to think that all material of Species A is stronger than material of Species B if, for example, average values are 10 to 15% different.

1. Specific Gravity and Density

The property values of wood increase with increasing specific gravity (SG). While density is a measure of weight per unit volume often reported with kilograms per cubic meter, SG is a dimensionless ratio of the density of wood at a specified moisture content to the density of water. Because changes in moisture contents result in dimensional changes, SG and density should be compared at the same moisture content. Specific gravity is an index of mechanical property values of wood free from defects; the higher the SG, the higher the appropriate property value. However, SG and density values for lumber are also affected by the presence of gums, resins, and extractives, which contribute little to mechanical properties.

2. Knots

A knot is that portion of a branch that has become incorporated in the bole of the tree. The influence of a knot on mechanical properties of a wood member is due to the interruption of continuity and change in direction of wood fibers associated with a knot. The influence of a knot depends on its size, its location, its shape, its soundness, and the type of stress measured.

Most mechanical property values are lower at sections containing knots. Knots generally have a greater effect on tensile strength than on compressive strength. For this reason, knots have their greatest influence in the tension zone when exposed to bending stress. The effects of knot size, type, and location are specifically addressed by the grading rules that specify limits for each commercially marketed species–size–grade combination.

3. Slope of Grain

The mechanical properties of wood are quite sensitive to fiber and ring orientation. For example, parallel-to-grain tensile or compressive strength property values are generally 10 to 20 times greater than those perpendicular to grain. Deviations from straight grain in a typical board are termed slope of grain or cross-grain. The terms relate the fiber direction to the edges of the piece. Any form of cross-grain can have detrimental effects on mechanical properties.

4. Juvenile Wood

During the first 5 to 20 years of growth, the immature cambial tissue produces wood cells with distinct variations in microfibril orientation throughout the important S_2 layer of the cell wall. This wood is referred to as juvenile wood. Juvenile wood exhibits excessive warpage because of anatomical differences within this S_2 layer of the cell wall. It also exhibits lower strength properties and becomes a problem within the wood industry because of the trend toward processing younger, smaller diameter trees as the larger diameter, old-growth stock becomes more difficult to obtain.

5. Creep

Wood is a viscoelastic material. Initially, it will act elastically, experiencing nearly full recovery of load-induced deformation upon stress removal. However, wood will experience nonrecoverable deformation upon extended loading. This deformation is known as creep. For example, the magnitude of additional creep-related deformation after a 10-year loading will roughly equal the initial deformation caused by that load. The rate of creep increases with increasing temperature and moisture content.

B. Environmental

1. Moisture Content

Mechanical property values of wood increase as wood dries from the fiber saturation point to 10 to 15% moisture content. For clear wood, mechanical property values continue to increase as wood dries below 10 to 15% moisture content. For lumber, studies have shown that mechanical property values reach a maximum at about 10 to 15% moisture content, then begin to decrease with decreasing moisture content below 10 to 15%. For either product the effects of moisture content are considered to be reversible in the absence of decay.

2. Temperature

Strength and stiffness decrease when wood is heated and increase when cooled. The temperature effect is immediate and, for the most part, reversible for short heating durations. However, if wood is exposed to elevated temperatures for an extended time, strength is permanently reduced because of wood substance degradation and a corresponding loss in weight. The magnitude of these permanent effects depends on moisture content, heating medium, temperature, exposure period, and to a lesser extent, species and specimen size. As a general rule, wood should not be exposed to temperatures above 65°C. The immediate effect of temperature interacts with the effect of moisture content so that neither effect can be completely understood without consideration of the other.

3. Decay and Insect Damage

Wood is conducive to decay and insect damage in moist, warm conditions. Decay within a structure cannot be tolerated because strength is rapidly reduced in even the early stages of decay. It has been estimated that a 5% weight loss from decay can result in strength losses as high as 50%. If the warm, moist conditions required for decay cannot be controlled, then the use of naturally decay resistant wood species or chemical treatments are required to impede decay. Insects, such as termites and certain types of beetles, can be just as damaging to mechanical performance. Insect infestation can be controlled via mechanical barriers, naturally durable species, or chemical treatments.

V. Properties and Grades of Sawn Lumber

At first, the highest quality level of sawn lumber might seem desirable for all uses, and indeed it is needed for several uses. However, in most situations, such material would be prohibitively expensive and a wasteful use of our timber resource. In practice, the quality level needed for a function can be easily specified because lumber and timber are graded in an orderly system developed to serve the interests of the users and the producers.

The grading system is actually several systems, each designed for specific products. Hardwood lumber is mostly graded for remanufacture, with only small amounts graded for construction. Softwood is also graded for both remanufacture and construction, but primarily for construction.

In practice, an orderly, voluntary but circuitous system of responsibilities has evolved in the United States for the development, manufacture, and merchandising of most stress-graded lumber and timber. In general, stress-grading principles are developed from research findings and engineering concepts, often within committees and subcommittees of the American Society for Testing and Materials.

For lumber, the National Institute for Standards and Technology cooperates with producers, distributors, users, and regional grade-rules-writing agencies through the American Lumber Standard Committee (ALSC). The ALSC has assembled a voluntary softwood standard of manufacture, called the American Softwood Lumber Standard. The American Softwood Lumber Standard and its related National Grading Rule prescribe the ways in which stress-grading principles can be used to formulate grading rules for dimension lumber (nominal 2 to 4 in. thick). This lumber standard is the basis for commercially marketing structural lumber in the United States.

For timbers (more than 5 in. nominal), the National Grading Rule does not apply. Thus, each regional grade-rules-writing agency publishes grade rules for timbers following the general principles of the National Grading Rule, but each differs slightly in eventual grade requirements and names. For further specifics on the various characteristics for the individual species-grade combinations, contact the individual grade-rules-writing organizations directly. In North America, those agencies are National Lumber Grades Authority (Vancouver, BC, Canada), Northeastern Lumber Manufacturers Association (Cumberland, ME), Redwood Inspection Service (Mill Valley, CA), Southern Pine Inspection Bureau (Pensacola, FL), West Coast Lumber Inspection Bureau (Portland, OR), and Western Wood Products Association (Portland, OR). [*See* FOREST TREE, GENETIC IMPROVEMENT.]

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Wool and Mohair Production and Processing

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Glossary

Fiber Unit of matter characterized by flexibility, fineness, and high ratio of length to thickness typically capable of being spun into yarn

Grade Fineness of wool and mohair fibers

Hair Usually straight, relatively brittle, and lustrous; stronger, smoother, and coarser than wool and generally lacks felting properties

Wool and mohair adjectives *grease:* fiber taken from the living sheep or Angora goat which has not been commercially scoured; *pulled:* fiber taken from the pelt of a slaughtered animal which has not been commercially scoured (synonym: slipe); *raw:* fiber in the grease, pulled, or scoured state; *recycled:* fiber that has been reclaimed from woven, knitted, or felted structures whether or not it was used by the ultimate consumer; *scoured:* fiber from which the bulk of impurities has been removed by an aqueous or solvent washing process; *virgin:* new wool fibers that have not been reclaimed from any spun, woven, knitted, braided or otherwise manufactured product

Woolen and worsted systems Two distinct systems for producing yarns with wool and mohair; woolen-spun yarns tend to be bulky with low twist and fibers lying in random directions; in contrast, worsted yarns are compact and highly twisted containing relatively long fibers that are more or less parallel to the longitudinal axis of the yarn; most short fibers are removed in a combing process

In the restricted context of this article, wool is defined as the fibrous covering of the sheep, *Ovis* species, and mohair is the fiber harvested from Angora goats, one breed within the *Capra* species. Thus, the term wool is much broader, encompassing fibers from all sheep breeds. In contrast, mohair is grown by a single breed of goat. Production and processing refer, respectively, to the quantities of fibers grown by these animals throughout the world and their conversion from a raw, agricultural commodity to a finished fabric whether it be a bolt of suit cloth or the covering material for a paint roller. In a broader sense, production encompasses all the genetic and environmental factors that influence the amount of fiber grown.

I. Origins of Domestic Sheep and Goats

A. Sheep

The domestication of sheep and goats was probably complete more than 11,000 years ago. At that time, fibers produced by wild sheep and goats bore little resemblance to modern, white finewools or mohair. Sheep were covered with coarse, medullated, colored hair with a trace of an undercoat of relatively fine, soft fibers of lighter shade. In all likelihood, the fibrous coverings of sheep and goats were probably similar in texture and appearance to many other species. Thus, it was not the fiber attributes that led to domestication but rather the convenience of accessible supplies of meat, skins, fat, bone, horn, and gut. The natural herding instincts of sheep and goats coupled with their abundance and their relatively docile nature no doubt recommended these species above all others to ancient man.

From skeletal remains, it is known that sheep had been domesticated as early as 9000 B.C. in the Zagras mountains where Iraq now borders Iran. In prehistory, people learned that wool could be felted to produce fabrics that could be tailored. They also learned to spin yarns and weave fabrics. Sometime long ago, the observation was made that imparting twist to a strand of fibers imparts strength. From this observation evolved the art and science of yarn making and subsequently fabric making by methods that include, among others, weaving and knitting. Development of the sheep fleece through selective breeding is highly correlated with the development of spinning and weaving from a craft to current industrial practices. Much of the selective breeding is totally undocumented. It is known that the coarse, colored fleeces of ancient sheep were shed once a year unlike the white, fine fleeces of modern sheep breeds. Some of the old-world breeds persisted to the present time and are represented by the Mouflon (of Corsica and Sardinia), the Bighorn Sheep (of the United States), Soay (St. Kilda, Scotland), and some of the hair breeds of India and Africa. Much of what we know about the early development of sheep has been deduced from ancient depictions of sheep in sculpture, relief, and paintings. Samples of wool fabric are available from about 1500 B.C. Some conclusions have also been drawn from ancient parchments made from sheepskin. In particular, the evolution of the sheep as a fiber producer has been followed to some degree by studying the primary and secondary follicles in the preserved skin. In ancient fleeces, the ratio of primary to secondary follicles was in the order of 1 : 3. Primary follicles produced coarse, medullated fibers. Secondary follicles, when active, produced fine, undercoat fibers. As sheep were selected for wool production, the ratio of primary to secondary follicles increased to 1 : 5 for present day medium wool sheep and as high as 1 : 25 for finewool-producing merino sheep. During this period of selection, primary follicles have become smaller and secondaries somewhat larger so that in today's finewool sheep, both types of follicle are producing fibers of comparable size. Further, the density of follicles in the skin has been increased from less than 10 mm^{-2} to as much as 80 mm^{-2} in very productive finewool sheep.

Wool-containing textile remains from Roman times are quite numerous. Generally, these have been shown to be composed of finewools (in remnants of clothing), medium wools (in blankets and rugs), and wools of intermediate fineness (in hosiery and knitwear). True finewool-producing sheep are thought to have been developed first in the Middle East which was, consequently, the site of early advances in textile technology. The products of this technology were distributed throughout the Mediterranean region and beyond by Greek and Phoenician sea-going traders. Greek legend concerning the golden fleece of Colchis dates to about 700 B.C. and this has been linked to the existence of fine wool since antiquity. The Romans conquered Great Britain in 55 B.C. and introduced the craft of wool textile manufacturing there and throughout Europe. Development of this art form and the subsequent wool industry was ultimately responsible for producing much of the wealth which resulted in the acquisition of the British Empire. Romans also introduced sheep to Spain which they considered to have an ideal climate for wool production. Following the fall of the Roman Empire about 600 A.D., written European history became almost nonexistent. Only with the advent of the European Renaissance in the 13th century can the development of sheep and wool production be followed. By this time, invaders of Arab origin had brought truly finewool sheep into Spain and, following expulsion of the Islamic Moors from Spain in 1491, development of the Merino breed is quite well documented. Merinos did not leave Spain until the 18th century at which time numerous European countries became recipients of this superior wool-producing breed. In the meantime, many other distinctive sheep breeds had been developed in Europe. All of these produced wool that was coarser but invariably longer than the merinos. Nevertheless, the wool of many breeds was fine enough to make clothing. Meat from sheep, wool, and wool textiles were extremely important to European economies. Great Britain introduced fine wool sheep in its South African and Australian colonies with a view to further increasing revenues from wool. The first importation of merino sheep into Australia occurred in 1793. However, the best documented importation occurred in 1797 from South Africa. Progress in selective breeding can be assessed in terms of wool production of the sheep. During the mid 1800s, fleece weights for sheep producing 20 μm wool were around 1 kg. Today, merino sheep producing the same grade would be growing more than 5 kg per year. This increase was achieved primarily by selecting for more dense and longer fleeces.

Domesticated sheep arrived in the New World with the first Spanish explorers and settlers. Most of these sheep were of the "churra" variety though some were merinos. Early Dutch settlers probably brought the first sheep to the east coast region of the United States but the policy of the English monarchs was to suppress production in the American colonies. This single policy was undoubtedly a major contributing cause of the American Revolution. After the Revolution, a concerted effort was made to improve the quality of wool produced in the United States. Finewool rams were imported primarily from Spain and France. As the pioneers moved westward, sheep trailed along with them serving a similar purpose to their forbearers on other continents 10,000 years earlier. Sheep numbers had increased to 53 million head by 1844 and peaked in 1942 when the population was 56 million. Since that time, numbers have declined to their present level of 11.2 million, two-thirds of which are in the western states and Texas. Nationally, sheep are of minor importance compared to cattle and hogs. However, sheep are still an important part of the agricultural economy in Texas, Wyoming, California, Montana, South Dakota, and several other states mainly because these ruminants (and goats) can constitute a profitable operation on land that is too poor to support cattle alone.

B. Angora Goats

Mohair is produced by a single breed of goat, the Angora, which was named after a Turkish province. The historical origin of the breed is still something of a mystery. One theory is that Angora goats evolved in the geographic region of present-day Turkey. However, the absence of any description of this type of goat by classical Roman or Greek authors would seem to undermine such a theory. A more likely hypothesis is that Angora goats arrived in Turkey with migrating pastoral tribes during the 11th century having originated in Central Asia. Perhaps derived from wild goats of Central Asia, e.g., *Capra falconeri*, Angoras were first described in Europe by Father Belon in 1554 after his travels through Asia Minor, including the province of Angora. Raw mohair reached Europe from Turkey in 1820. The expertise for producing pure mohair textiles was generated over time using the worsted system as a basis. As the demand for mohair increased, Angora goats were eventually released from Turkey. South Africa received its first importation in 1838 and by 1893 a major industry involving nearly 3 million goats had been established. In 1848, the first Angora goats were imported into the United States. Here, the growth of the industry was much slower than in South Africa. By 1900, less than 0.25 million Angora goats were present in the United States. With the major producers being Turkey, South Africa, and the United States in this century, mohair production has fluctuated widely, mainly as a result of fashion changes. [*See* GOAT PRODUCTION.]

II. Distribution of Sheep and Angora Goats throughout the World

The world population of wooled sheep in 1991 was 1160.4 million. The numbers of sheep in the major producing regions are shown in Table I. Australia leads with 166.2 million followed by the former Soviet Union (134.6 million), China (115.2 million), and New Zealand (55.2 million). During this period, the United States reported 11.2 million.

The world population of Angora goats was approximately 5.4 million in 1991. Table II shows the population and production in seven countries. South Africa is the leading producer followed closely by the United States with over 90% of the mohair production being in Texas.

III. Production and Consumption of Wool and Mohair

A. Wool

In the period 1991–1992, world wool production was 3.01 million tonnes (metric tons) greasy wool which is equivalent to approximately 1.74 million tonnes of clean wool. In general terms, this amount was composed of 52.9% merino wool, 23.3% cross-bred wool, and 23.8% carpet-type wool. Production by country is summarized in Table I. The world's largest production and the main source of apparel wools entering international trade channels is from Australia.

TABLE 1
World Wooled Sheep Population and Wool Production (1990–1991)[a]

Country	Sheep population (million)	Raw wool production (1000 tonnes, greasy)	Wool production (1000 tonnes, clean equiv.)
Albania	1.6	3	1
Argentina	26.9	136	82
Australia	166.2	1066	699
Brazil	20.1	27	19
Bulgaria	7.1	26	11
Canada	0.8	2	1
Chile	5.3	20	12
China	115.2	240	120
Czechoslovakia	1.0	5	3
Falkland Islands	0.7	3	2
France	11.1	23	13
Germany	3.2	21	11
Greece	10.2	10	6
Hungary	1.9	7	3
India	40.0	35	21
Iran	34.0	32	14
Iraq	7.8	17	7
Irish Republic	9.1	17	11
Italy	10.8	14	6
Lesotho	1.5	3	1
Mongolia	14.3	20	11
Morroco	16.2	35	14
Namibia	6.7	1	1
New Zealand	55.2	305	228
Pakistan	30.2	63	26
Peru	12.3	10	7
Poland	3.9	15	8
Portugal	3.4	9	5
Romania	14.1	33	15
South Africa[b]	25.0	106	63
Former Soviet Union	134.6	471	212
Spain	24.0	42	19
Turkey	47.5	83	42
United Kingdom	43.9	72	48
United States of America	11.2	41	22
Uruguay	25.9	94	62
Yugoslavia	7.4	10	5
Other African countries[c]	126.9	111	51
Other American countries[d]	25.1	22	11
Other Asian countries[e]	51.7	68	34
Other Western European countries[f]	6.4	12	7
World total	1160.4	3330	1934

[a] *Source:* International Wool Textile Organisation.

[b] Includes estimated Bantu production.

[c] Other African countries include: Algeria, Botswana, Egypt, Ethiopia, Kenya, Libya, Mali, Mozambique, Sudan, Swaziland, Tanzania, Tunisia, Zambia, and Zimbabwe.

[d] Other American countries include: Bolivia, Columbia, Ecuador, Greenland, Mexico, Paraguay, and Venezuela.

[e] Other Asian countries include: Afghanistan, Bangladesh, Bhutan, Cyprus, Gaza, Indonesia, Israel, Jordan, Kuwait, Lebanon, Macao, Malaysia, Myanmar, Nepal, Saudi Arabia, Syria, Thailand, and Yemen.

[f] Other Western European countries include: Austria, Belgium, Denmark, Finland, Iceland, Luxembourg, Malta, Netherlands, Norway, Sweden, and Switzerland.

TABLE II

World Angora Goat Population and Mohair Production by Main Producing Countries (1991)

Country	Angora goat population (1000's)	Mohair production (greasy, mkg)
Argentina	183	0.6
Australia	183	0.6
Lesotho	152	0.5
New Zealand	91	0.3
Turkey	365	1.2
South Africa	2284	7.5
United States of America	2071	6.8
Other countries	61	0.2
Total	5390	17.7

Source: International Mohair Association and Mohair Council of America.

Australia's production fell 17% in 1991–1992 to its lowest level since 1985–1986. Reduction in sheep numbers and wool production are attributed to relatively low financial returns for wool and movement of producers to other agricultural enterprises. Wool production also fell in Argentina, Uruguay, the former Soviet Union, South Africa, and New Zealand. In contrast, wool production in China, Pakistan, the United Kingdom, and the United States was relatively static. The carry forward of unsold wool stocks into 1991–1992 from Australia, New Zealand, South Africa, Argentina, Uruguay, and the U.K. was a record 719,000 tonnes (clean equivalent).

Consumption of virgin wool is shown in Table III. Following two successive years of decline, wool consumption increased by 6% in the calendar year 1991 to about 1.63 million tonnes clean. Strong growth in consumption was noticed primarily in China (+50%) and also in South Korea (+24%), Taiwan (+139%), Italy (+13%), and the United States (+22%). For the first time on record, China became the world's largest user of wool. Consumption in the former Soviet Union and in Eastern Europe declined by 7 and 26%, respectively, probably as a result of the political turmoil in these areas. With wool becoming more competitively priced compared to synthetic fibers, wool consumption is expected to increase during the next few years. It remains to be seen if this trend will be strong enough to cause a turnaround in sheep numbers and wool production. Drought in some of the major wool growing areas and low returns in 1992 and 1993 may persuade some growers to stay out of the business permanently.

B. Mohair

In recent years, world mohair production peaked in 1988 when 25.95 million kilograms (mkg) was produced. Since that time, a reduction in world demand for mohair coupled with a prolonged drought in South Africa have resulted in a decline in production which is estimated to be 16.85 mkg in 1992. Table II shows world mohair production for the calendar year 1991. South Africa has been the major producing country since 1976. Prior to that year, the United States and South Africa alternated the lead. In 1992, the United States again became the world's leading mohair producer. In contrast, production in Turkey, the historical home of mohair, has been declining steadily for many years while the relatively small amounts of production in Argentina and Lesotho have been fairly constant. Australia and New Zealand initiated mohair production in the early 1980s, reporting 0.5 and 0.05 mkg, respectively, in 1984. Production increased for a few years and remained constant at 1.0 and 0.5 mkg between 1988 and 1990 before declining quite drastically in 1991. Accurate records of worldwide mohair consumption by country are not available. Table IV shows the countries to which U.S. mohair was exported in 1991.

Large fluctuations in the demand for mohair and consequently prices paid are accepted phenomena in the mohair business. Despite promotional efforts by the International Mohair Association (IMA), these dramatic changes in demand, production, and prices seem to be permanent fixtures because mohair is, first and foremost, a fashion fiber. When designers utilize lustrous fabrics with a brushed, hairy appearance for a particular fall or winter season, the outlook for mohair is bright. The primary challenge to the IMA and others with investments in the mohair industry is to develop products with year-round, long-term appeal. With such products, the oftimes devastating effects of cyclical demand, with production lagging 2 or 3 years behind, might be overcome.

IV. Major Wool Producing Sheep Breeds

The position of sheep among animal vertebrates is shown below:

Class	*Mammalia* (mammals, those which suckle their young)
Order	*Ungulatae* (hoofed mammals)

TABLE III

Consumption of Virgin Wool by the Wool Textile Industry at the Spinning Stage (1991)

Country	Wool consumption (1000 tonnes-clean basis)	Country	Wool consumption (1000 tonnes-clean basis)
Afghanistan	11.250	Korea (South)	60.145
Algeria	21.500	Libya	1.650
Argentina	29.535	Macao	2.000
Australia	16.871	Malaysia	1.924
Austria	6.438	Mauritius	2.236
Belgium	33.800	Mexico	6.700
Bolivia	4.940	Mongolia	9.120
Brazil	5.300	Morocco	18.250
Bulgaria	10.594	Nepal	9.200
Canada	4.707	Netherlands	4.800
Chile	6.962	New Zealand	17.066
China	250.424	Norway	2.290
Columbia	3.455	Pakistan	28.855
Czechoslovakia	16.348	Peru	4.400
Denmark	2.995	Poland	11.130
Ecuador	1.000	Portugal	14.321
Egypt	4.460	Romania	13.413
Finland	0.550	Saudi Arabia	1.400
France	23.777	South Africa	4.446
Germany	59.073	Former Soviet Union	234.900
Greece	12.435	Spain	22.887
Hong Kong	5.973	Sweden	0.413
Hungary	2.658	Switzerland	11.626
Iceland	0.498	Syria	11.500
India	33.000	Taiwan	30.399
Iran	21.722	Turkey	62.499
Iraq	4.480	United Kindgom	71.268
Irish Republic	8.168	United States	62.638
Israel	0.720	Uruguay	6.348
Italy	155.090	Venezuela	0.800
Japan	116.719	Yugoslavia	14.719
Jordon	1.000		
Kenya	1.224	Total	1621.008

Source: International Wool Textile Organisation and International Wool Secretariat.

Suborder	*Artiodactyla* (even-toed ungulates)
Section	*Pectora* (typical ruminants)
Family	*Bovidae* (hollow-horned ruminants)
Subfamily	*Caprinae* (sheep and goats)
Genus	*Ovis* (sheep)
Species	*Ovis aries* (domesticated sheep)
	Ovis ammon (Argali)
	Ovis canadensis (North American Bighorn)
	Ovis orientalis (Urial)
	Ovis laristanica (Urial)
	Ovis musimon (Moufflon)
	Ovis tragelaphus (North African Aoudad)
	Ovis vignei (Asiatic Urial)

Breeds that belong to the species *Ovis aries* number over 500 but can be categorized into five groups by the type of wool they produce. These are: fine-wool, medium-wool, long-wool, crossbred-wool, and carpet-wool type of sheep. Within species there are also substantial variations in other traits, e.g., size and shape, color of wool, horns, and type of tail.

A breed can be defined as a group of sheep with a common origin and certain physical characteristics that are readily distinguishable. Wool characteristics of several important breeds are presented in Table V.

V. Fiber Composition and Growth

In its raw state, the keratin of sheep and Angora goat fibers is coated with variable amounts of wax and

TABLE IV
United States Exports of Greasy Mohair (1991)

Country	% of total
United Kingdom	55
India	16
Taiwan	12
Belgium	9
Italy	4
Hong Kong	1
Germany	1
Others	2

Source: Mohair Council of America, 1992.

suint which in turn are contaminated to varying degrees with dirt, plant parts, urine, feces, and other miscellaneous materials. The amounts of wax and suint are somewhat genetically controlled while the contaminants are almost totally influenced by the environment. The waxes which protect the fibers against water and sunlight damage are composed of a mixture of esters and constitute 2–30% of the weight of greasy fibers. These esters are condensation products of water-insoluble alcohols (23) and higher fatty acids (36). The complex chemical characteristics of wool wax have been described. The purified form of wool wax is known as lanolin. The term "yolk" refers to the combination of wax plus suint. By convention, suint is defined as the portion of the yolk that is soluble in cold water. It consists primarily of a mixture of potassium salts of fatty acids (C_5–C_{16}) and is present in amounts varying from 2 to 15% of the greasy fleece. Suint is composed of 30–40% inorganic matter and 60–70% organic material. Other metal ions present in suint include sodium, calcium, and magnesium. Inorganic anions present in suint ash include carbonate (primarily), chloride, sulfate, phosphate, and silicate.

Not including the 0.5% or so of inorganic material, cleansed wool and mohair have the following approximate analysis: carbon, 50%; oxygen, 22–25%; nitrogen, 16–17%; hydrogen, 7%; and sulfur, 3–4%.

The basic chemical building blocks of wool and mohair are 19 amino acids. These compounds are carried to the point of fiber synthesis in follicles in blood, at which point the amino acids are polymerized to form a complex mixture of polypeptides which is called keratin. Individual polypeptide molecules are composed of many amino acid molecules attached end to end through peptide bonds. Free amino and carboxylic acid groups at the end and along the length of these long molecules contribute to the dyeing behavior of wool and mohair. Individual molecules are covalently attached to other polypeptide chains via disulfide bonds contained in the amino acid cystine. In addition, adjacent molecules are bonded together through ionic, hydrogen, and Van der Waals attractions. All these bond types contribute to the strength and elasticity of wool and mohair fibers. At the molecular level, polypeptide molecules are arranged in the form of α-helices. Stretching a wool or mohair fiber below the point at which it will break results in the breaking of many hydrogen and Van der Waals bonds and the helix form changes to β. When the fibers are released from extension, contraction to original length is accompanied by a return to the α-helix structure. The ability of wool and mohair textiles to return to their original dimensions after physical distortion is a direct consequence of the physical changes that can occur in the α-helix structure. At the molecular level, areas of molecular organization (crystalline regions) and disarray (amorphous regions) have been observed using X-ray techniques.

In wool and mohair fibers, the protein keratin is contained in two types of cell that constitute the microstructure. These are called cuticle and cortical cells. Cuticle cells are readily observed through the light microscope and appear as platelike scales on the fiber surface that are laid down in an overlapping fashion. Much variability exists in scale size and shape among fibers of varying diameter and between species. Nevertheless, the topography of these animal fibers is unmistakable and has never been artificially synthesized. In very fine wool fibers, individual cuticle cells overlap each other and form a complete ring around the circumference of a fiber like a stack of crowns ("coronal" arrangement). In coarser fibers, overlapping of corticle cells is still apparent but several cells circumscribe the fiber ("imbricate" arrangement). In coarse wool and mohair, cuticle cells appear to be arranged in a mosaic ("reticulate" arrangement) with minimal overlapping of individual cells being apparent. This arrangement of cuticle cells is responsible for the increased luster observed in mohair and some coarse wools (Lincoln and Leicester, for example) compared to finewools. Three distinct regions (epi-, exo-, and endocuticle) have been isolated and defined in the cuticle.

Cortical cells compose the cortex of the fiber and are much longer (80–100 μm) than they are wide (3–5 μm). These cigar-shaped cells are themselves composed of macrofibrils which in turn are made up of microfibrils. It has been postulated that the microfibrils contain 11 protofibrils and that each protofibril is composed of three polypeptide molecules

TABLE V

Breed Classification by Fiber Diameter, Wool Production, and Staple Length

	Range of average diameter (μm)	Grease fleece wt. range, ewes (kg)	Range of staple length (mm)
Finewool breeds			
Superfine Australian merino	<18	3–4	75–90
Fine Australian merino	19–20	3–5	80–100
Medium Australian merino	21–22	4–6	90–100
Strong Australian merino	23–26	5–7	100–130
Cormo	19–23	4–5.5	100–130
Rambouillet	19–24	4–7	60–100
Debouillet	18–22	4–7	75–125
Medium wool breeds			
Dorset (horned and polled)	26–32	2–3.5	75–100
Finnsheep (Finnish Landrace)	24–31	2–3.5	75–100
Hampshire	25–33	2.5–4.5	60–100
Oxford	28–34	3–4.5	75–130
Romanov	28–33	2.5–6	100–125
Ryeland	26–32	2–4	75–100
Shropshire	25–33	2–4.5	80–100
Southdown	23–29	2–3.5	50–75
Suffolk	26–35	2.5–3.5	75–100
Texel	28–33	3–4.5	70–100
Wiltshire Horn	40–80	1	20–30
Long wool breeds			
Border Leicester	30–40	4.5–6	150–250
Cheviot	26–33	2–3	75–130
Coopworth	35–39	5–7	150–250
Cotswold	33–40	5.5–7	200–300
English Leicester	37–40	5–6	150–280
Lincoln	39–48	5.5–9	250–300
Romney Marsh	32–39	4.5–8	125–220
Crossbreed wool type breeds			
Columbia	23–30	5.5–7.5	100–150
Corriedale	25–33	4.5–7	100–180
Montadale	25–30	3–5	75–125
Panama	25–30	6–7	75–125
Perendale	28–35	3–6	100–180
Polwarth	23–26	4–5.5	75–110
Polypay	24–31	3–4.5	75–125
Targhee	21–25	4.5–6.5	75–125
Carpet wool breeds			
Drysdale	35–45	5–7 (6 month)	100–150 (6 month)
Karakul	25–36	2–4.5	150–300
Navajo-Churro (Undercoat)	22–24	2–3.5	140–150
(Outercoat)	37–47	(both coats)	200–350
Scottish Blackface	28–38	2–3	250–350
Also, numerous Asiatic types including fat-tail and fat-rump sheep			

in an α-helix arrangement (Fig. 1). In the microstructure, cortical cells are differentiated by physical and chemical properties into ortho and para cells. In crimped fine wool, the *ortho* cortical cells are concentrated on the outside of each curve, para cells being on the inside. In order to accommodate this arrangement along the length of a fiber, the structure must continuously twist (Fig. 2). In coarse wool and mohair, ortho cells tend to be surrounded by para cells. Thus, the distribution of ortho and para cells in wool and mohair is associated with the presence (or absence) and type of fiber crimp.

Crimp in wool and waviness in mohair are readily observable in the macrostructure. Using a light microscope, three distinct regions can be readily distinguished in fibers that have never been shorn and were

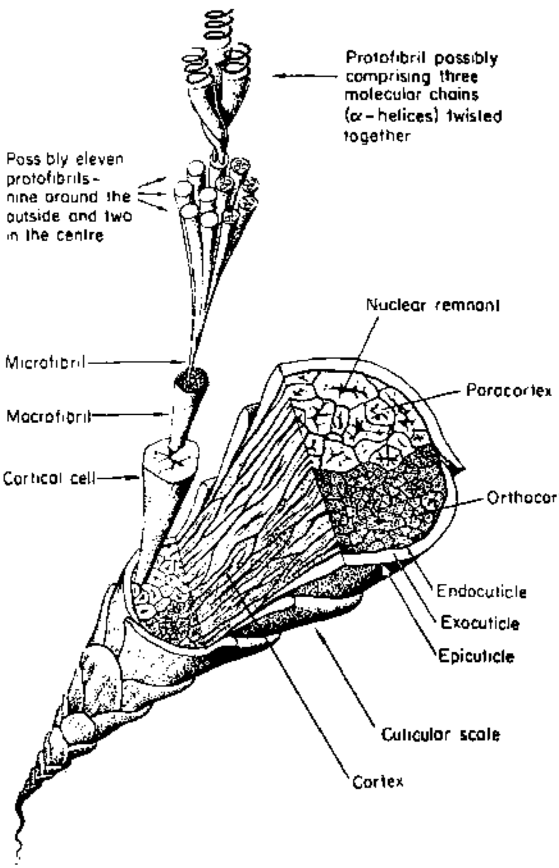

FIGURE 1 Possible structure of wool. [After Ryder, M. L., and Stephensen, S. K. (1968). "Wool Growth." Academic Press, London.]

plucked out of the skin rather than shorn. These regions are referred to as "tip," "shaft," and "root." After the first shearing, tips no longer exist. Thus, fibers shorn after the first shearing are composed entirely of shaft since the root portion is left in the animal. Even in these fibers, variations in diameter exist along the length of individual fibers, these being related to nutrition and health factors during the period of fiber production.

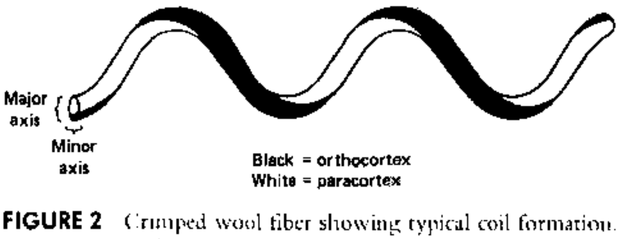

FIGURE 2 Crimped wool fiber showing typical coil formation. [After Botkin, M. P., Field, R. A., and Johnson, C. L. (1988). "Sheep and Wool: Science, Production, and Management." Prentice-Hall, Englewood Cliffs, NJ.]

One further component that is readily observable in the cortex of some fibers is the medulla. This portion of the fiber consists of a network of hollow, air-filled cells in which the cell walls may have collapsed to form a partially or completely hollow, strawlike fiber. Medullated fibers are common and often desirable in coarse wool but are considered a serious fault in mohair. Medullated fibers in which the medulla diameter constitutes more than 60% of the fiber diameter are termed "kemp." Kemp fibers appear not to accept dyestuff and are thus easily distinguished as white, chalky fibers in dyed fabrics. At least three types of medullation are distinguished: fragmented, interrupted, and continuous (Fig. 3).

Skin functions as a single organ although it contains cells arranged in multiple tissues (blood vessels, connective tissue, epidermis, follicle, glands, and muscle) and composing intercellular material (e.g., lymph and connective fibrous material). Since fleeces from different sheep breeds and Angora goats differ in so many respects, it follows that the dimensions and composition of fiber-producing organs in these animals also exhibit marked differences. The study of the structure of these tissues is termed, "skin histology." A simplified, three-dimensional representation of fiber-producing cells in the skin appears in Fig. 4. The various zones of the follicle concerned with the functional stages of fiber formation are shown in Fig. 5. Blood supply to the papilla provides nutrients for fiber formation. The follicle bulb is one of the most active dividing tissues in the body. The proteins that compose keratin are formed in the keratogenous zone and are keratinized in the final hardening zone. The sebaceous gland and the sweat (or suderiferous) gland excrete wax and sweat, respectively, which diffuse over the fiber surface in the pilary canal. Coarse-wooled sheep and Angora goats produce less wax than fine-wooled sheep (e.g., karakul, 2.35%; merino, 14.3–16.1%). The arrector muscle has an inactive role in sheep but may influence crimp.

Two types of follicle have been distinguished in histological studies, primary and secondary. A primary follicle is shown in Fig. 5. Secondary follicles are similar in appearance but do not have sweat glands or arrector pili muscles. The development of follicles has been studied for sheep and Angora goats. In merino sheep, follicles are distinguishable in 60-day-old fetuses. All primary follicles produce a keratinized fiber by 108–110 days of fetal development. Some secondaries produce fiber by 120–145 days of development. Post-natal development of the remaining secondary follicles is rapid concluding about 6 months

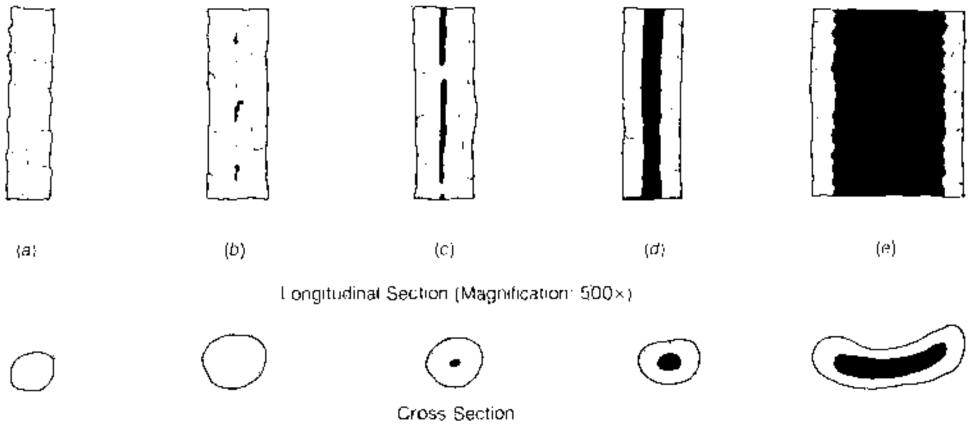

FIGURE 3 Types and degrees of medullation in wool and mohair fibers.

after birth. The rate of development and number of secondary follicles formed during this time can be greatly affected by available nutrition. Even under optimum conditions of nutrition, a small percentage of the secondary follicles may never fully develop. In general, fibers produced by primary follicles are coarser than those produced in secondaries. The difference in average diameter between fibers produced in secondary compared to primary follicles is minimal for finewool breeds and substantial for coarse wool breeds and Angora goats.

Follicles lie at an acute angle in the skin surface. Generally groups of three primary follicles ("the trio") are associated with a specific number of secondary follicles, this number being very variable among breeds and between species. Within a breed, the ratio of secondary (S) to primary (P) follicles is somewhat variable with high S:P ratios being associated with high wool or mohair production of relatively fine fiber and vice versa.

VI. Breeding and Selection for Wool and Mohair

A. Sheep

In sheep, fleece traits are relatively high in heritability compared to reproductive and growth traits. Staple length and fiber diameter are both highly heritable (Table VI) whereas measures of fleece weight, yield, crimp, and luster fall in the medium or low to medium heritability categories. Occasionally, a black lamb occurs in a white flock. More commonly, a predominantly white lamb is born with a black spot in its fleece or on its eyelid, ear, leg, or foot. This important fault in white finewool sheep appears to be inherited and is most commonly explained by the existence of a pair of recessive genes. Many variations in color are present in the sheep population and, with few exceptions, are due to differences in genetic makeup rather than environmental influences. Even in finewool sheep breeds, some lambs are born with hairy fleeces. The hair is usually shed before weaning. The presence of hair in the fleece, particularly in the region of the britch is a fault and is considered to be highly heritable by most sheep breeders. In Rambouillet and other finewool breeds, the appearance of wool grown on the belly is quite different from that grown elsewhere in the fleece. Belly wool is typically shorter, lower yielding, and contains different crimp than wool in the bulk of the fleece. When this type of wool extends beyond the belly, it is considered to be a fault since overall fleece weight is reduced. This trait is considered to have medium heritability. [*See* ANIMAL BREEDING AND GENETICS.]

Fleece traits correlate with each other to varying degrees. Most of the traits are positively correlated. Thus, selection for increased fleece weight is expected to also result in increased fiber length, for example.

TABLE VI
Heritability Estimates for Sheep Fleece Traits

Trait	Estimated range of heritability (%)
Grease fleece weight	30–40
Clean fleece weight	30–40
Yield of clean wool	30–40
Staple length	40–50
Fiber diameter	30–50
Crimp	20–30
Luster	20–30

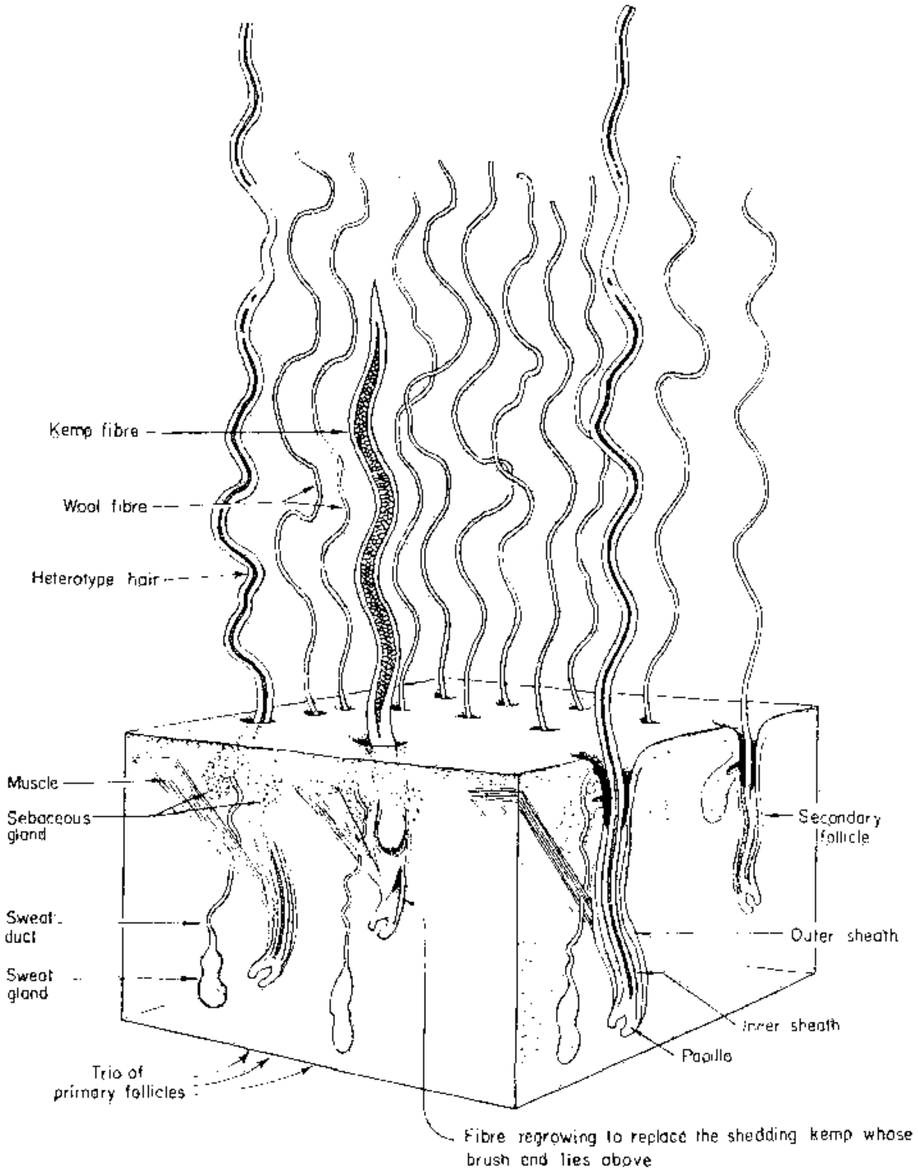

FIGURE 4 A simplified three-dimensional drawing of the structure of adult sheep skin. [After Ryder, M. L., and Stephenson, S. K. (1968). "Wool Growth." Academic Press, London.]

Unfortunately, the positive correlations of other traits with fiber diameter mean that selecting for one trait will result in an increase in average fiber diameter, this being particularly undesirable in finewool breeds. Conversely, selecting for finer wool will be expected to result in reduced fleece weight. A knowledge of correlations between fleece traits is a key factor in successful selection for more productive sheep. The situation is further complicated when traits not concerned with wool are taken into consideration, particularly in the so-called dual-purpose breeds where meat production is also a major factor. Selection for wool traits can be counterproductive for meat traits and vice versa.

Traditionally and in many flocks today, sheep are selected for wool traits using subjective methods, i.e., using the senses of sight and touch. Since objective methods are more accurate, progress can be accelerated by using measurements made with instruments. In large flocks, this may not be economically feasible so selection emphasis is placed primarily on the potential male stud animals that are subsequently used to breed many ewes. Superior young males are often identified using performance

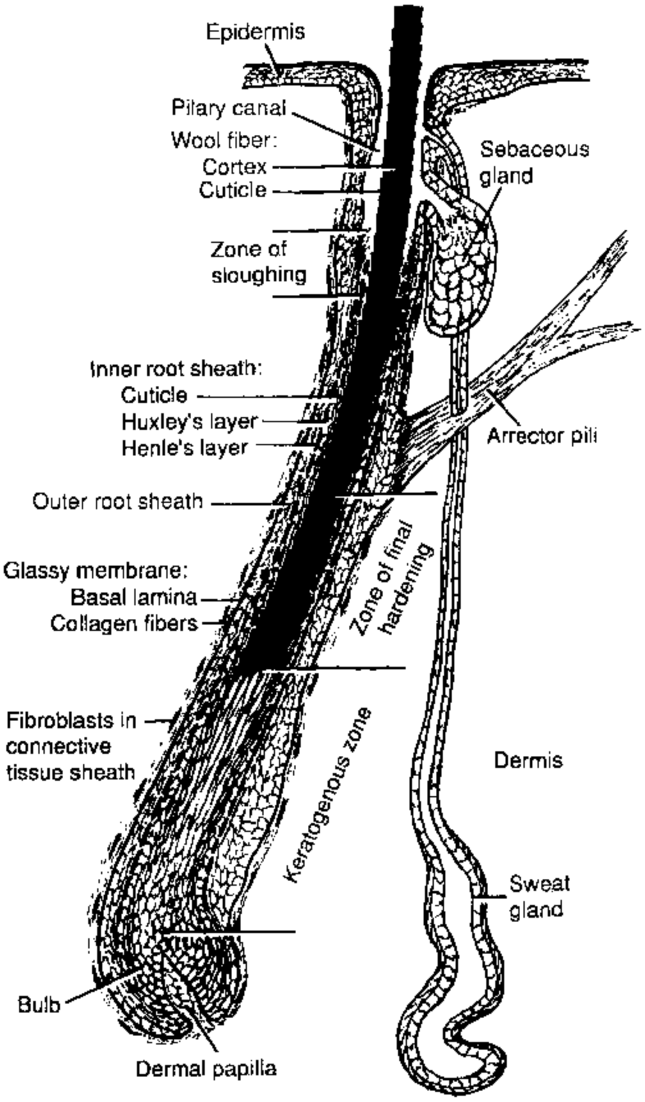

FIGURE 5 Diagram of a primary follicle with a nonmedullated wool fiber. [After Chapman, R. E., and Ward, K. A. (1979). "Physiological and Environmental Limitations to Wool Growth." University of New England, Armidale.]

tests. Since wool traits are not perfectly heritable, desired changes are rarely achieved in one generation. Change in a particular trait that can be expected between generations may be predicted by multiplying selection differential by heritability. When average change in a particular trait for a ewe flock is being considered, then generation length must also be taken into account. Obviously, if ewes are being retained in a flock for 8 years, progress will be slower than if the generation interval were 3 or 4 years. Selection is not only practiced to alter or improve traits but is necessary to maintain optimized production traits.

B. Angora Goats

Angora goats are raised primarily for their mohair. Production of meat from older animals or young cull goats is of secondary importance. Thus, the emphasis in selection is almost entirely on mohair production and quality. However, some attention must be paid to body conformation in order to retain functional, productive animals capable of surviving under harsh range conditions.

As with sheep, the amount of mohair grown in unit time is positively correlated with animal weight and fiber diameter. Selection for larger animals is desirable for several reasons. The greater skin area provides more sites for mohair production and larger size is positively associated with ease of kidding, fertility, and number of kids born and raised. However, size of goat must be balanced with fineness of mohair produced since only a small market exists for excessively coarse mohair. In addition to these factors, increased staple length, luster, style (number of twists per unit length in staple), and character (number of waves per unit length in staple) of mohair are traits assessed and selected for in Angora goats. Since medullated fibers constitute a serious fault, their presence in mohair is vigorously selected against using visual and objective techniques.

VII. Central Performance Tests

Since some meat production and wool traits are negatively correlated and since most wool and mohair traits require objective measurement for efficient selection, it is difficult for many sheep and Angora goat producers to properly identify potential stud animals. Central performance tests for sheep breeds in which wool production is important are typically conducted during the fall and winter months. Rams born the previous spring or fall are entered into these tests since testing animals that are younger than this does not give an accurate indication of future wool production or quality. Typically, body growth rate as well as wool traits are measured over a 4- to 6-month period while all the animals being tested are maintained under uniform conditions. Thus, central performance tests may be used as a basis for within- and between-flock selection of sires. Since the cost of testing animals is quite high, most cooperators in these central tests are pure breeders. However, the positive effects of the performance tests are also shared to some degree with commercial producers who purchase their replacement rams and billie goats from the pure-bred breeders.

Ranking of animals in performance tests is normally accomplished using an index equation since several traits, rather than a single trait, are being considered. For finewool, dual-purpose breeds such as the Rambouillet, the index contains such factors as daily body weight gain and final body weight in addition to the wool traits. Each trait is weighted in the index according to heritability, economic importance, and desired selection pressure.

Increased wool or mohair production may be achieved by selecting for increased fiber diameter, fiber length, and/or total number of fibers covering the body surface. This latter trait is most commonly estimated by measuring fiber density (or producing follicles per unit area) and estimating body surface area. Increases in fiber length, density, or body surface result in proportionate increases in clean wool production. Since volume is proportional to the square of fiber diameter, and weight is directly proportional to volume, it follows that doubling fiber diameter results in a fourfold increase in clean fiber production. Because of the price structure, it is not always economically advisable to increase mohair or wool production by selection for increased fiber diameter even though this is the most efficient way to do it.

The selection index equations used in the Texas Agricultural Experiment Station performance tests are as follows. For finewool rams:

Index value = 60 × [daily body weight gain in pounds] + 4 × [staple length in inches with no credit above 5.5 in.] + 4 × [12 months clean fleece weight in pounds adjusted for initial body weight] − 3 × [face cover score] − 4 × [skin fold score] with ± fiber diameter and variability points according to the following schedule. Fiber diameter on the side; −3 for each micron (μm) or fractional value above 22.9 μm and +3 for each μm or fractional value below 22.0 μm. Variability between side and britch diameter; −2.5 for each μm the britch is coarser than the side with no advantage if the britch is finer than the side wool.

For Angora billie goats the equation is

Index value = 4 × [clean fleece weight in pounds adjusted for initial weight] + 25 × [average daily body weight gain in pounds] + 0.12 × [final weight in pounds] + 3 × [straightened lock length in inches] − 1.5 × [average fiber diameter in μm] − 3 × [face cover score] + 2.5 × [character score] + 1.5 × [neck cover score].

Similar indices are being used in all the major wool and mohair production areas throughout the world to assist producers in selecting the most productive sires.

VIII. Environmental and Health Management Aspects of Fiber Production

A. Nutrition

Nutrient requirements of sheep and Angora goats are met primarily by native or improved ranges, fields, pastures, and crop residues. However, when these are not available or when it is desirable (e.g., fattening lambs for the meat market) diets are formulated and fed to support desired production levels. In the United States, excellent sources of detailed nutritional information for sheep and Angora goats are the National Research Council's (NRC) bulletins on recommended nutrient allowances. Specific information is presented on energy (total digestible nutrients, digestible energy, and metabolizable energy), crude protein, mineral, and vitamin requirements for many different categories of sheep and Angora goats. In addition, these bulletins list detailed compositions for sheep and goat feeds. These include: forages and roughages; pasture, range plants, and forages fed green; silages; energy feeds, protein, and mineral supplements. [*See* ANIMAL NUTRITION, RUMINANT; FEEDS AND FEEDING.]

The physical dimensions and hence the amount of wool and mohair produced by sheep and Angora goats are dependent upon the nutrition status of the animal. Generally, as the quality and quantity of available nutrition declines, fiber diameter and fiber length decrease resulting in lower wool and mohair production. The effects of short-term deficiencies in nutrition that may exist toward the end of pregnancy, when the fetus has a high demand on available nutrients, can have a substantial effect on wool fiber diameter and staple strength. The demands on a ewe during the last stages of gestation and during lactation are often so great that nutrients available for wool production become inadequate. At such times, the diameter of the fiber being produced can be reduced so dramatically as to cause a tender spot or "break" that affects the whole fleece. This defect in wool can greatly undermine its value particularly when a break exists close to the center of the staple, causing the broken halves to be too short for worsted processing. When a break occurs close to one end, this constitutes a less serious fault, but much short wool will be lost in carding and combing. The constitution of a female Angora goat (doe) is quite different from most ewes. When shortages of nutrition exist, the does tend to continue mohair production at rates close to optimal. Before fiber production is reduced significantly, the doe is more likely to abort her fetus. Hence, tender mohair, or mohair with breaks in the staple, is very unusual. It should be noted that disease and illness can also cause drastic changes in fiber diameter and production and that nutrition inadequacies are not always the cause of these problems in wool or mohair. Weak points in animal fibers are sometimes associated with radical changes in diet (e.g., from pasture to feedlot) or ingestion of poisonous plants. Even under optimal production conditions, finewool ewes raising a lamb will shear 10–20% less wool than one that is "dry." Similarly, ewes raising twin lambs will shear at least 5% less wool than ewes raising single lambs. These numbers are variable among breeds.

If a ewe or doe is undernourished during late pregnancy or lactation, there is little chance that her offspring will ever fulfill its maximum potential for fiber production. Only limited initiation and maturation of primary and secondary follicles occur in an undernourished fetus, lamb, or kid. No amount of feeding after the first few months of the animals life can correct this situation.

In relation to their size, Angora goats produce more fiber than Rambouillet sheep. Efficiency of fiber production is almost twice as high for the Angora goat compared to the Rambouillet sheep. Specific information is available in the technical literature on the effects of nutrition on wool and mohair production. There is a greater magnitude of wool data than mohair information. Nevertheless, knowing the breed (genetic background) of sheep and goats, their age and weight, conditions under which the animals are maintained, and health status and having specific knowledge of the type and quantity of food ingested, the amount and average diameter of fibers produced can be predicted with fair accuracy.

B. Flock Management

Several other aspects of environmental management influence the quality of wool and mohair production. Improperly designed feeding systems can result in fleeces contaminated with hay, pellets, and other feedstuffs. Improper pasture use results in fleeces heavily infested with plant seeds and parts. Ideally, sheep and goats are removed from contaminating pastures during the period when grass and plant seeds are falling and attempts are made to remove the objectionable plant species from the range. This is achieved by using combinations of chemical, mechanical, and fire treatments in addition to strategic grazing. Sometimes the problem of fleece contamination with vegetable matter can be avoided by heavy grazing of plants before seeds mature.

Colored fiber contamination is a serious problem in white wool and mohair. This problem can be minimized by shearing off all urine- and fecal-contaminated fibers sometime before shearing proper. This management practice, known as "tagging," is quite common in the sheep but not in the Angora goat industry. Most producers make an effort to remove colored fibers at shearing time. Connected with this issue is removal of belly fibers from the fleece. It has been shown that removal of belly wool from finewool sheep fleeces significantly reduces colored fiber counts in products made from the wool. Fibers from other animal species probably contribute to colored-fiber content of the belly wool. Separation of "belly mohair" is not a common practice in the United States.

Other fleece contaminants that the textile industry has focused on in recent years include polypropylene and branding paint. Polypropylene has many agricultural uses. Polypropylene twine is used to tie hay bales and polypropylene and polyethylene ribbon are used in the manufacture of some brands of feed sacks. Unfortunately, it finds its way into wool and mohair fleeces. With the characteristic of fibrillating when processed mechanically, it is invariably apparent in the final product where it constitutes a serious fault. Producers can eliminate the polypropylene contamination problem by removing all known sources of this contaminant from areas where sheep and goats are grazed, penned, and sheared. In some countries and locations within the United States, paint branding of sheep is required by law. To avoid permanent discoloration of the wool, producers should use only the recommended brands of "fully-scourable" paint. Failure to do so results in reduced value of the fiber.

Theoretically, shearing sheep and goats before lambing and kidding, particularly when the animals are moved indoors to give birth, results in cleaner, less contaminated fleeces. Many sheep producers are not prepared to follow this practice, mainly for environmental reasons. However, this is normal practice for Angora goats. However, shearing should be close to parturition since often the associated fever causes a temporary cessation of keratin production which manifests itself as a weak point in the fiber. The closer this weak point is to the base or tip of the fiber, the more value it will retain.

When accompanied by wind, heavy rain immediately after shearing can lead to disastrous livestock losses. High conduction heat-loss can affect animals within 30 min. The rapid chilling puts the freshly shorn animal into irreversible shock. Angora goats are more susceptible to this problem than sheep. However, it can be serious for both species. This problem can be avoided by providing shelter to animals immediately after shearing when weather conditions are unfavorable.

C. Health Management

Internal and external parasite infestation has been shown to reduce wool and mohair production. Even moderate populations of external parasites undermine the quality and appearance of wool and mohair since animals tend to entangle their fleeces as they rub to reduce skin irritation. Good managers ensure minimal infestation through regular and strategic drenching and spraying with anthelmintics and pesticides. Since animal health generally affects wool and mohair production and quality, successful managers also make conservative use of vaccines and antibiotics in their cost-effective health programs. Great variation exists among the health management practices of individual producers. On one extreme is the individual who has great concern for the well-being of the animals. At the other end of the spectrum is the producer who regards the animals simply as economic units.

Other health problems that have a direct effect on fiber quality and quantity are diseases of the skin. These can occur when the skin is damaged, e.g., at shearing or by plant-seed puncture, and becomes infected. Since treatment is not often feasible for individual animals in large flocks, the untreated infection can eventually cause death, more often through dehydration, since a very sick animal may not walk far to water. Mycotic dermatitis is an infection of fleece-zone skin that when left untreated, results in "lumpy" wool and possible death. Antibiotics can be used to treat this disease. [*See* ANIMAL DISEASES.]

Another skin disease that arises when sheep and goats remain wet for several days is caused by the bacterium *Pseudomonas aeruginosa*. Under warm, wet conditions, the bacteria multiply rapidly and give rise to a condition known as fleece rot. The wool and mohair are usually colored green/blue due to deposition of the pigment pyocyanine. This pigment is not easily scoured and constitutes a serious fault. In addition, affected fleeces smell badly and this attracts blow flies. Thus, fleece rot is often the cause of a fly strike. The larvae feed on the wet wool adjacent to the skin, causing fiber to detach. Affected animals are shorn completely and affected areas are treated with ointments, sprays, or powders.

Skin infections often result in abscesses in lymph nodes. *Caseous lymphadenitis* produces green pus in these abscesses. Although these do not usually adversely affect fiber production, their presence can cause carcasses for meat to be condemned.

Scab (scabies or mange) affects sheep and goats. Several types of minute mites are responsible for this condition. The mites live on tissue serum and cause intense itching. Thus, the wool or mohair is typically rubbed off by the irritated animal and scaly lesions appear. Affected animals become emaciated and anemic. Specific miticides are recommended by veterinarians.

IX. Physical Properties and Characterization

Fleece and fiber characteristics of white wool and mohair that are of primary importance to the worsted industry are: yield, including quantity and type of vegetable matter; average fiber diameter; average staple length; staple strength and position of break; color; and proportion of colored fibers. In the case of mohair, the proportion of medullated fiber and the amount of luster are also of primary importance. Traits of secondary importance include: variability of fiber diameter, variability of staple length; proportion of matted fibers (cots); and resistance to compression. Other value-determining characteristics include: presence/absence of weathered tips; age/breed/type; style; character; and handle. Most of these properties can be measured with instruments which makes the measurements "objective." Some properties can only be assessed using human judgment, which is "subjective" measurement. Individual batches of wool and mohair are variable in all of the properties listed. Variability exists in individual staples and even within single fibers. Thus, methods were developed to sample wool and mohair to obtain representative samples. These methods fall into two categories, core sampling and grab sampling, the latter being used when staple length must be preserved. Packages of greasy or scoured fiber are typically core-sampled with tubes measuring 2.2 cm ($\frac{7}{8}$ in.) or, in the United States, 5.1 cm (2 in.) in diameter. These samples are used to measure all the listed characteristics except for length.

Standard test methods and practices of the International Wool Textile Organisation (IWTO) and the International Mohair Association (IMA) are used throughout the world to characterize the physical properties of wool and mohair. In addition, most producing and manufacturing countries maintain their own national test methods. In the United States, these methods are under the jurisdiction of the American Society for Testing and Materials (ASTM).

Wool and mohair fibers are hygroscopic, meaning they are capable of absorbing moisture and losing it when the humidity or temperature of the surrounding atmosphere changes. Despite this property, which relies on gaseous adsorption and desorption of water vapor, the fibers themselves are measurably water repellant due to the lipophilic surface of the epicuticle. The ability of wool and mohair to retain moisture without feeling wet is responsible for many of the associated comfort properties. It also makes it necessary to specify the temperature and humidity at which fibers are tested since temperature and moisture content affect most physical properties. Standard conditions of testing for wool and mohair are 20°C and 65% RH throughout the world. When wool and mohair are equilibrated under these conditions after being "bone" dried, the fibers contain less moisture than when they are conditioned from the wet side. Convention requires, therefore, that fibers be dried prior to testing, yield testing being the exception.

The standard test methods for yield have changed little since their introduction. Basically, the methods involve scouring greasy samples in hot, soapy water followed by determination of residual grease, inorganic ash, and vegetable content of the dried and scoured fiber. Wool or mohair "base" can be calculated from these data. Various factors may be applied to the base yield to incorporate standard amounts of moisture and permitted tolerance levels of ash and grease. These methods are accurate but tedious. Near infrared reflectance spectroscopy is being investigated as a potential replacement.

After yield, average diameter is the most important value-determining factor of wool and mohair within a specific length category. Fiber diameter and length determine the fineness of yarn that can be spun from a particular batch of fibers. In fact, old subjective methods for expressing fineness of wool and mohair use a system composed of yarn sizes to indicate fiber fineness (e.g., 30's to 80's for wool and 18's to 40's for mohair). The numbers refer to the number of 560 yard hanks in one pound of the finest yarn that can be spun from that fiber. Increased speed of processing and worsted spinning are making these values obsolete and the numbers have only theoretical value now.

Internationally, microprojection techniques for determining fiber fineness and distribution (in microns = one millionth of a meter) have been the standard for many years. Although accurate, these methods are slow and tedious and have been replaced in many testing facilities by air-flow instruments. Airflow is relatively fast and accurate but is not capable of measuring distribution of fineness. Modern technology (e.g., computers, lasers, and automatic image analysis) is currently being evaluated to provide rapid measures of these important fiber diameter traits. Staple length determines primarily which system will be used to spin the fibers, i.e., worsted, woolen, or short staple. A highly significant linear relationship exists between staple length of sound greasy fibers and average fiber length in top. This, in turn, has a major influence on spinning capabilities. Traditionally, manual means have been used to quantify length and length distribution. However, semi-automated, photoelectric methods are now available to determine this characteristic more rapidly. Staple strength is a major determinant of yarn strength. Several instruments were developed for measuring the strength of individual, greasy staples and even fibers. Current state-of-the-art instrumentation for measuring staple length and strength is the Automatic Tester for Length and Strength (ATLAS). This instrument is being used commercially to provide presale staple length and strength data for Australian wools.

The color of greasy wool and mohair is not strongly correlated with clean wool color or whiteness. Thus, wool and mohair are washed before this characteristic is determined. The presence of colored (yellow, brown, and black) fibers in white wool and mohair constitutes a serious fault and greatly undermines value since the fibers are no longer suitable for use in white or pastel textiles. Because colored fibers are usually in very low concentration and not uniformly distributed throughout accumulations of wool or mohair, testing for their presence in greasy samples does not usually produce an accurate answer. After scouring and mechanical processing, all the homogenizing that takes place up to top production provides a structure (the top) in which colored fiber content can be determined with accuracy. This is normally determined by counting the number of colored fibers in unit weight of top. Image analysis techniques are being investigated to provide an objective measurement of this undesirable trait. Because of difficulties involved in obtaining a representative sample, it is doubtful that an objective method of measuring dark fibers in greasy wool or mohair can be developed.

Visual appraisal of crimp frequency and definition in wool has been used to estimate average fiber diameter and resistance to compression. Instruments are available for more accurate determinations. Resistance to compression provides a measure of the bulkiness of wool which is very important to manufacturers of sweaters, carpets, and futons.

There is currently no objective measure of luster in wool or mohair. However, luster visually assessed in the clean portion at the greasy staple base provides a reasonable estimate of the degree of luster that will be present after scouring. Medullation, particularly in carpet wools and mohair, is an important measurable characteristic. In carpet wools, medullation is a desirable trait. In mohair, kemp fibers (medullation greater than 60% of fiber diameter) represent a serious fault. An instrument was developed for measuring total medullation in wool and mohair (the Medullameter) but it is incapable of differentiating between med (medullation less than 60% of fiber diameter) and kemp fibers, the latter being much more undesirable than the former. Thus, the basis for most medullated fiber measurements is still the projection microscope, although again, an image analysis technique is being developed to provide a faster result.

In mohair terminology, style and character of greasy staples refer to the twist (ringlets) per unit length and the number of waves per unit length, respectively. Although these traits are normally assessed subjectively, they can be painstakingly measured with a ruler. The amount of style and/or character in mohair is thought to be indicative of the length and length variability that can be obtained in top after mechanical processing. These relationships have not been quantified.

Many physical properties of wool and mohair are usually invariable and therefore, not measured routinely on individual lots. Such properties include elasticity, conductivity of heat, flammability, felting propensity, durability, softness, resistance to soiling, and drape. Keratin fibers are noted for their ability to recover from stretching, a property that is attributable to the cell structure and chemistry of the fibers. Elasticity is important for the comfort and ease of care (including shape retention and crease shedding) of garments made from wool and mohair. Wool and mohair do not readily conduct heat. Thus, when knitted or woven into clothes, the tiny pockets of air formed in the fabric structure serve to keep the body at a reasonably constant temperature in both excessively hot or cold climates. Wool and mohair do not burn readily when exposed to a flame and are self-extinguishing when the heat source is removed. Thus, wool and mohair are ideal fibers in end-uses that require flame retardance such as children's sleepwear, wallcoverings, carpets, and upholstery. The natural flame retardance of wool and mohair alone or in blends with natural and synthetic fibers can be enhanced by application of chemicals.

When subjected to intermittent pressure and heat in the presence of moisture, fabrics composed of wool mat or felt to varying degrees. This property is a direct result of the scale structure in the cuticle which gives rise to the "differential frictional effect" and which is not so apparent in the relatively smooth mohair fibers. In addition to commercial felts, felting is essential to obtain the required effect in a broad spectrum of wool fabrics ranging from minimal felting in worsted suitings to a significant amount in brushed woolen coating materials.

Wool and mohair are extremely durable. Protected from moth, chemical, and mechanical damage, textiles composed of these fibers are longlasting. The longevity of mohair upholstery pile fabrics used in public transportation is legend. Generally, the coarser the fiber, the longer the product will resist wear. Coarser fibers are normally restricted to use in carpets, upholstery, and outerwear whereas the finer, softer grades are used in garments that are worn next to the skin. Softness is particularly important in textiles composed of woolen yarns for which many users have an expectancy for comfort and softness. In such end-uses, many synthetic fibers and the coarser types of wool and mohair simply cannot perform. Unlike nylon and polyester, wool and mohair do not permit build-up of static electricity except under very dry conditions. The anti-static properties also contribute to the resistance to soiling of wool and mohair textiles. Further, the bright colors of dyed wool and mohair fabrics can easily be returned from soiled textiles by either aqueous or solvent cleaning. However, care must be taken in the case of wool to avoid matting or felting shrinkage.

The term "drape" refers to the way a fabric hangs from or around the object it is covering. Wool and mohair fabrics are considered to have excellent drape when used in a range of products from high quality suitings, to drapes, to outerwear garments. The drape and grace exhibited by wool and mohair in well-tailored suits are seldom surpassed using fabrics composed of synthetic fibers.

X. Specialty Wool and Mohair

An increased demand for colored wool has resulted from the re-emergence, growth, and popularity of handcrafts including handspinning, weaving, and knitting. Specialized markets exist throughout the world, but particularly in Europe and the United States, for properly prepared colored fleeces that exhibit the attributes desired by handspinners. More recently, a demand has also been created for naturally colored mohair. Although goat geneticists might deny the existence of a colored gene in purebred Angora goats, the fact remains that a few colored goats are born, even in tightly controlled Angora goat flocks. Thus, in the United States and Australia, small flocks of these colored Angora goats have been established and are being maintained and bred specifically for the handcraft trade. The range of available colors in mohair, which include black, brown, taupe, and gray, is far less than the broad spectrum available in wool. Besides color, other desirable features of fleeces intended for the handspinning market include adequate length (>10 cm), structural soundness of fibers (no breaks), and freedom from stains and vegetable matter defect. Fleeces coarser than 25 μm with distinct crimp and luster seem to be most popular with handspinners.

Another form of specialty wool is the so-called "superfine" wool currently being produced in Australia under the auspices of the Sharlea Society. Sheep in range flocks are selected for their ability to produce wool finer than 18 μm and longer than 85 mm. These sheep are sheared, fitted with protective coats, and kept indoors eating carefully controlled diets. The wool produced is extremely fine, clean, strong, and uniform and commands high prices at auction. About 50,000 kg were produced in 1990 with Japanese textile firms being the major buyers. This type of wool is used to produce suitings and knitwear of the highest quality. On a smaller scale, New Zealand also has enterprises with coated sheep, but in that country the sheep are maintained on pasture.

Certain breeds of sheep grow wool that is not often used in the mainstream of textiles or constitutes only a small proportion of the whole. Although these wools are not necessarily expensive, they are regarded as specialty products. Further, modern marketing methods have done much to enhance the reputation of erstwhile ordinary wools, e.g., British wools, to the point where they are now sold as specialty wools. Similar marketing methods are being practiced in countries of origin to enhance the reputations of mohair, e.g., "Texas" and "Cape" mohair. Thus, it is somewhat difficult to differentiate between a true specialty product and a good marketing ploy. The specific attributes of wool produced by different sheep breeds were discussed previously.

Historically, mohair with excellent style (i.e., ringlet staples) has been carefully hand scoured and dried to produce "hair" for dolls. Although this business is relatively small, it does exist. Only long, clean, white, lustrous staples may be used in this product.

Lastly, some of the most specialized wools come from sheep that have been selected and bred specifically for carpet-wool production. Such breeds include the Drysdale, Tukidale, Elliotdale, and Carpetmaster that produce straight, heavily medullated (>20%) wool in a range around 40 μm. These wools, though excellent in carpets, have little or no utility outside of these products and are produced primarily in New Zealand but also in the high rainfall areas of Australia.

XI. Shearing, Preparation, and Classing

Most sheep are shorn once a year thus providing wool of adequate length for processing on the worsted system. Some breeds of sheep (e.g., Drysdale) and Angora goats grow wool and mohair so fast that it is shorn at 6-month intervals and still has adequate length for worsted processing. In hot climates where high atmospheric temperatures are thought to impair lamb production, some sheep are shorn twice or even three times a year, thus producing short wool which is suitable only for processing on the woolen, cotton, or short-staple systems.

Methods of removing wool and mohair from the animals vary among countries. The shearing method that has evolved for sheep in Australia and other major wool producing countries involves maneuvering the animal through a sequence of positions in which it is comfortable but essentially immobile. In this way, the skin is kept tight while the majority of the fleece is removed in one piece using electric shears or clippers. In countries influenced by Spanish culture, including the United States, following removal of belly and some leg wool, the legs of sheep and Angora goats are tied together before the bulk of the fleece is removed. In South Africa, many Angora goats are still shorn with hand shears. Research into chemical and robotic shearing of sheep has been undertaken for years. To date, no economical shearing method has been devised to replace manpower.

Facilities for shearing sheep and goats vary considerably among and within countries. In the major wool-producing countries, most ranches, stations, and farms have permanent facilities, typically consisting of a complex arrangement of pens and a substantial building (Fig. 6) containing more pens, a shearing floor, and room to sort and package the wool or mohair. Sheep and goats in other countries, including many locations in the United States, are shorn in temporary shearing facilities or buildings that are used for other purposes during the remainder of the year. Whatever the physical plant, shearing is usually contracted by the producer since it is a highly skilled profession. Permanent damage can be done to the animal and the fibers if untrained shearers are used. In the United States, shearing facilities span the whole spectrum from tents or tarps set up on the open range, to dirt floors in the corner of barns, to customized shearing trailers, to Australian-style shearing facilities. Whatever the facilities, some precautions are usually followed before shearing and are generally the producer's responsibility. Sheep and goats are held in clean, dry pens or small pastures (traps) without feed and water for 12 hr prior to shearing. The animals are not bedded down on straw or hay since this contaminates the fibers. The producer provides enough laborers to deliver the animals to the shearers and to handle the fleeces and sheep or goats after shearing. However, many shearing companies offer a turn-key job and provide this labor, tables for skirting, skirters, classers, and wool balers. It is to the producer's advantage to organize all these details prior to the day of shearing.

Traditionally, wool and mohair were shorn and the whole fleece was placed into some kind of receptacle (e.g., a large jute bag), packaged, and sold. The different qualities or grades of fiber in a single package were not separated until it arrived at a textile mill or custom sorting facility. However, adding value to these fibrous commodities is now an objective of most wool and mohair producers in the world. Thus, wool and mohair fleeces are often skirted and classed prior to packaging and marketing. Skirting is the practice of separating all inferior fleece portions such as belly fiber, urine-stained, and fecal-contaminated fibers from the bulk of the fleece immediately after shearing (Fig. 7). The products of skirting wool are termed "skirted wool" and "skirts." There are several categories of skirts separated for their different compositions and values. The term more commonly used when applied to mohair is "preparation" but implies essentially similar treatment of the fleece. After the different components have been separated, the bulk of the fleece is classed. This means that skirted fleeces are grouped according to (visually assessed) fineness, yield, vegetable matter content and type, staple length, strength, and color. In the United States, the term "grading" means grouping fleeces according to average fiber diameter. However, some confusion exists and the terms "grading" and "classing" are used interchangeably (but incorrectly) by many people. When classing

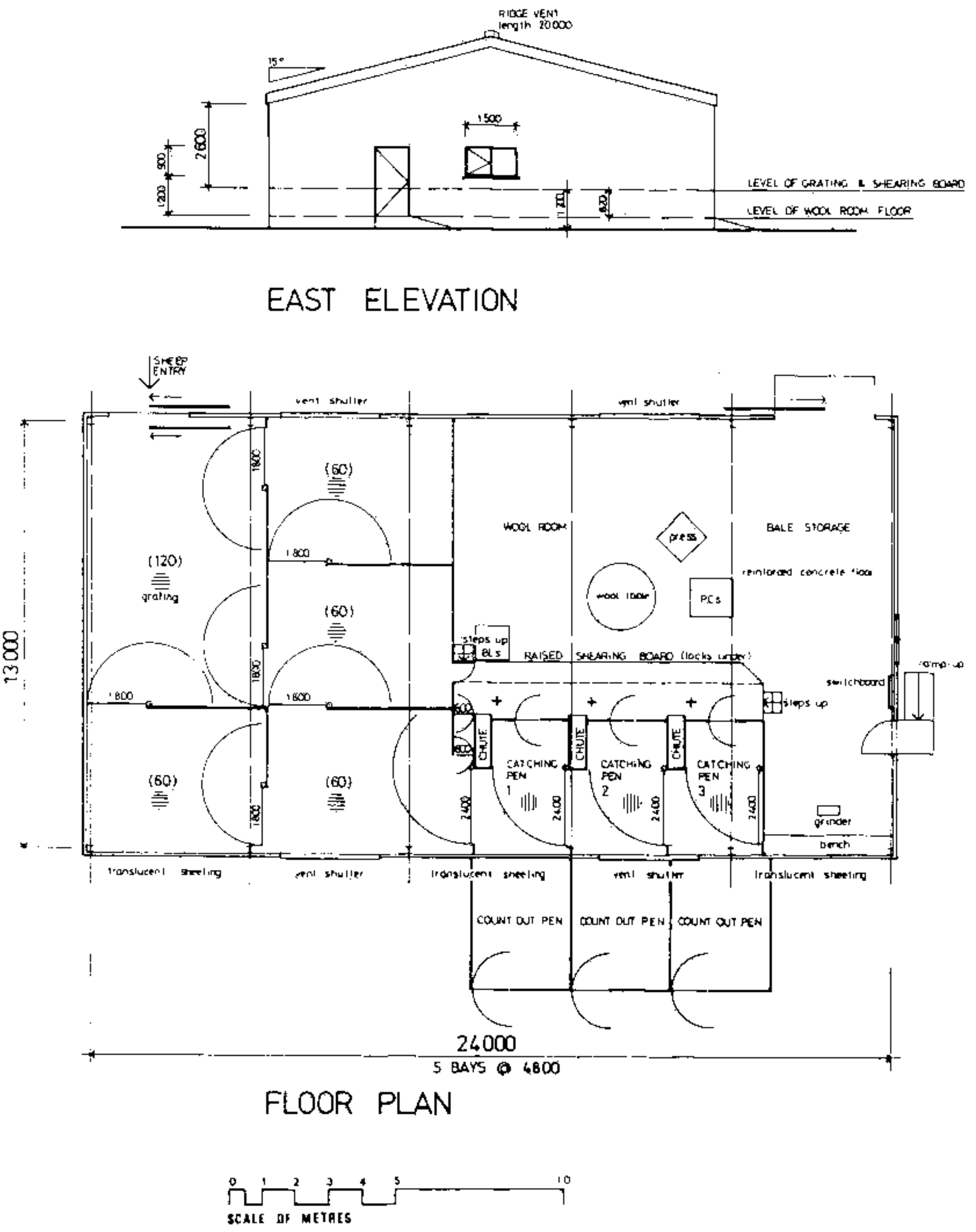

FIGURE 6 A three-stand Australian style shearing shed design. [Adapted from Wool Harvesting Notes. Wool Research Trust Fund, Sydney. 1982. Plan No. 4310.]

is performed at a brokerage firm or textile mill by highly trained personnel, the process is called "sorting." Long-term experience in Australia, New Zealand, and South Africa together with recent research studies and actual use in the United States, have shown that skirting and classing of wool immediately after shearing are indeed value-adding procedures for the producer. The same cannot be said for mohair, although preparation and classing are standard procedures throughout South Africa. In Texas, much of the mohair is packaged directly without skirting but simply grouping fleeces by animal age, e.g., kid, young goat, adult. Fleeces packaged in this way are known in the trade as "original bag" mohair.

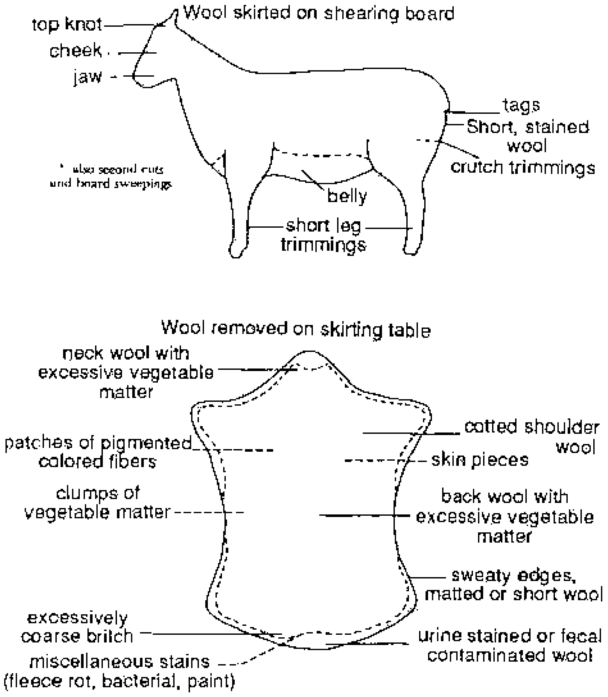

FIGURE 7 Wool skirting. [After Lupton, C. J., Pfeiffer, F. A., and Blakeman, N. E. (1989). "Optimizing the value of grease wool through preparation and marketing." *SID Res. J.* **5**, 2.]

In the major wool-producing countries, wool is packaged in bales. Fleeces placed in older types of baling machines are manually pressed through a system of mechanical levers whereas the newer versions are driven by electric or gasoline motors that hydraulically press the wool. Both systems are capable of producing bales of uniform size and weight (200 kg). Elsewhere in the world, many other forms of packaging exist. In the United States, for many years the standard form of packaging has been burlap sacks measuring between 1.8 and 2.5 m in length. These sacks are capable of being manually or mechanically packed. However, the density of the resulting package is much lower than a bale. Since wool bags are awkward to stack and cannot be efficiently packaged in shipping containers, five or six bags are typically baled together in the warehouse prior to shipment. Progressive producers and warehouses in the United States are now using Australian-style balers. In South Africa, the whole mohair clip is baled. In contrast, most of the U.S. clip is packaged in jute bags. Traditionally, baling material has also been composed of jute. However, polyethylene and polypropylene bale covers are now being used since they are considered to result in less contamination of the wool within the bale. The issue of jute versus hydrocarbon divides the wool industry at this time since advantages and disadvantages exist for both fiber classes. Whatever the form, the outside of the package is usually inscribed with enough information to identify the source of the wool or mohair, the type or class of fiber, classer (if used), and the number of the sack or bale.

XII. Marketing of Wool and Mohair

In this context, marketing is considered to be the aggregate of functions involved in moving the fibrous raw materials from producer to textile manufacturer. Thus, method of selling is just one part of the overall marketing strategy. For both wool and mohair, broad spectra of marketing methods exist, even within a single country. It is beyond the scope of this article to cover all known marketing methods for wool and mohair. Rather, some of the simplest and some of the more innovative will be considered. In the United States, a proportion of all wool and mohair is prepared for sale simply by shearing it from the animal, packaging whole fleeces in jute bags, and transporting the bags to warehouses or cooperatives. Such packaged products, known as "original bag," are made available for inspection to buyers who purchase the fiber after making subjective assessments. In contrast, an increasing proportion of U.S. wool and mohair is skirted and classed on the farm or ranch during shearing. Bales containing single classes of wool are delivered to warehouses where they are core-sampled prior to storing. Typically, the core samples are tested for clean yield and average fiber diameter, and this information is made available to potential buyers at the time of sale. This method of marketing wool (and mohair) in discrete classes and with objective measurements is modelled on methods developed in Australia. South Africa and New Zealand also market their wool and mohair in a similar manner.

Until recently, Australia and New Zealand both used floor-price schemes in an attempt to stabilize wool prices. A period of good demand and high prices for wool was followed by overproduction and decreased demand which culminated in early 1991 in the collapse of these schemes in Australia and New Zealand, but not in South Africa. Wool and mohair in that country is still purchased by national marketing boards when auction prices fall below predetermined levels. However, the major wool-producing countries (and the United States) now have "free" markets which once again are subject to rapid fluctuations in price.

Major sectors of the Australian wool industry are the growers, brokers, buyers, testers, "dumpers," processors, and the Australian Wool Corporation (AWC). The growers raise the sheep and have them sheared by some of the 13,000 unionized shearers. Shorn wool is classed by some 35,000 registered woolclassers, the majority of whom are trained producers who prefer to class their own wool. The different lines are then packed into bales and delivered to the broker. Woolbrokers act as agents for the growers in the sale of their wool. There are about 30 brokers in Australia handling the majority of Australian wool that is sold by auction. In addition to warehousing the grower's wool, the broker obtains representative grab and core samples for display use and for testing of core and grab samples by the Australian Wool Testing Authority (AWTA). The test information is made available to buyers prior to the time of sale. The broker is also responsible for organizing and advertising auctions, conducting the financial transactions, and arranging for the physical delivery of the wool. Other optional services available to the grower include bulk classing and reclassing, blending of lots, and sampling of wool not sold under the sale by sample scheme.

Wool-buying firms purchase wool through the auction system for individual overseas mills, a variety of clients, Australian textile companies, and speculatively for their own accounts. In addition, private buyers travel the country purchasing wool directly from growers. Less than 20% of Australian wool is sold outside the auction system via private treaty.

The AWTA provides accurate, impartial testing services in an attempt to "maximize net income to the Australian wool industry by encouraging the optimum application of objective measurements by woolgrowers, brokers, buyers and processors."

The wool dumping section of the industry compresses the farm bales into more compact bales, usually just prior to shipment, thereby minimizing freight costs.

The AWC was incorporated in 1973 having responsibilities associated with marketing and domestic promotion of the Australian clip. Funds are provided by a levy on proceeds from wool sales. The AWC participates in and makes recommendations for wool research conducted by Australian and international agencies. In addition, the AWC is also charged with maintaining the quality of clip preparation. This is achieved through the operation of a voluntary, woolclasser registration scheme, a clip inspection service, and general extension work.

In Great Britain, marketing techniques are quite different. Nearly all the fleece wool is sold through the producer-operated British Wool Marketing Board (BWMB) which was established in 1950. The Board arranges for wool received from the farmer to be classed at a central location and then sells it to the trade at auction. The Board is also responsible for fleece improvement and wool preparation programs and policies and promotion of wool sales. The Board sponsors wool research and product development. Without the BWMB, the vast majority of producers selling individually could not hope to obtain full market value for their small, variable clips. The system appears to be working well since, for its type, British wool regularly commands the highest price in the world.

Each year, the government establishes a guaranteed price for British wools after consultation with the farmers' unions. The Board then estimates its marketing costs and deducts this from the overall guaranteed price. A schedule of maximum prices for all grades is then prepared and made available to producers in April, prior to shearing time. This schedule of prices reflects changes in the relative market prices of different grades from the previous year and results in the payment of an average price to all producers of a particular grade who present their wool in the recommended manner. The effect of this pricing mechanism is to eliminate short-term price fluctuations to producers while passing on long-term market differentials. When the proceeds of the Board's wool auctions exceed the amount paid to producers in any one year, the excess goes into a reserve account. When the situation is reversed, money is withdrawn from the reserve or borrowed from the government. Special arrangements are made with the government to avoid excessive accumulations of debts or credit balances.

In the United States, most wool and mohair is sold through commission warehouses, cooperatives, and wool pools. Some wool and mohair is still sold directly by producers to order buyers, independent warehouses, or representatives of textile firms. In recent years, there has been a trend in both the wool and mohair sectors for marketing organizations to band together to offer larger accumulations of classed wool and mohair matchings. For wool, the U.S. Wool Marketing Association is leading the way in innovative marketing while the U.S. Mohair Marketing Board is serving a similar role for mohair. Public auction, though popular for livestock, is not a common method of selling wool and mohair in the United States. Despite recent attempts to use this method of sale, sealed bid, direct, private treaty, and forward contract remain the predominant methods of sale.

XIII. The National Wool Act in the United States

Recognizing wool as an essential and strategic commodity, the Congress of the United States established the National Wool Act in 1954 to provide wool and mohair producers with price stability and financial incentives to keep producing and improving the quality of their products. Today, more than 125,000 families consider that raising sheep and goats is an important part of their ranching/farming operations. Since low-cost wool imports continue to threaten the livelihoods of these people and many more thousands of U.S. textile workers, the existence of the Wool Act is still of vital importance to them. The program also has a self-help aspect. Producers have the option to give up a portion of their incentive payment to fund promotional and market development programs for wool, mohair, and lamb, operations which are now coordinated by the American Sheep Industry Association (ASI) and the Mohair Council of America (MCA). The incentive program is funded by tariffs on imported wool and mohair, both raw materials and textiles. For example, in 1988, $435 million was collected in wool tariffs. Producers received $86.4 million in incentive payments and $348.6 million remained in the U.S. Treasury. The National Wool Act makes it economically possible to produce wool and mohair in the United States today. It is surprising, even to other agricultural commodity groups, that the program is able to function without any direct cost to the U.S. taxpayer. On the contrary, the mechanism put into place to fund the incentive program invariably produces excess funds available for other taxpayer-supported programs.

According to the Act, a certain price is set each marketing year to encourage increased production and improved quality. This national support level is set by the Secretary of Agriculture. A second formula based on the historical value of wool production of lambs is used to determine the average price to be paid for the weight of wool on unshorn lambs marketed. Sheep and goat raisers that participate in this program must file sales receipts at their local Agricultural Stabilization and Conservation Service office for all their wool and mohair sales within a specific calendar year. This permits calculation of a national average price for wool and mohair. Subsequently, the national incentive levels are calculated.

For example, if the national support level is set at $1.81/lb and the actual weighted average price of U.S. wool is $0.87/lb, then the national incentive level will be 108% (i.e., $1.81 $0.87 = $0.94; ($0.94 ÷ $0.87) × 100 = 108%). Thus, a producer selling his wool for $1.00/lb will also receive an incentive payment of $1.08 (less ASI deductions). The greater the price received for wool, the greater incentive payment, up to a limit of four times the national average price. Thus, the Act provides a real incentive for the production of more and higher quality wool. The mohair program works in a similar manner. However, the actual support level set for mohair is invariably different (and higher) than that established for wool. There is no incentive payment on unshorn Angora goats.

In 1993, the U.S. government decided to phase out this incentive program over a 3-year period. This action is expected to have a short-term negative effect on the viability of the sheep and goat industries.

XIV. Scouring

Wool and mohair in bales or baled bags are allowed to "bloom" (recover from high compression) before opening. Opening is a mechanical cleaning process in which compressed fleeces are transformed into individual staples. A significant amount of loose dirt and vegetable material is removed in this process. Wool and mohair are scoured (washed) before further mechanical processing to remove as much of the nonkeratinous material as possible with minimal entanglement of the fibers. Suint, being soluble in water, is easily removed. Wool and mohair waxes are emulsified in aqueous solutions at temperatures above the melting point of the waxes (>50°C). Traditionally, solutions of soap and sodium carbonate were used to emulsify waxes from natural fibers and to stabilize the resultant emulsions. Commercially, soaps have been replaced by more efficient nonionic detergents. Cleansing of the fibers is achieved as the fibers are raked slowly through a sequence of four to six scouring baths. Intermediate squeezing between high-pressure rollers minimizes contamination from one bath into the next. Grease levels are reduced to below 1% (typically 0.4–0.8%) in the scouring process, and residual detergent is rinsed out in the last scouring bath, this being composed of clean, warm water only. The slow action of the rakes, essential to avoid felting or matting of wool, belies the large throughput of scouring trains. Modern, 2-m-wide minibowl scouring trains are capable of cleansing more than 1400 kg of greasy wool per hour (= > 1000 kg/hr of New Zealand crossbred wool). Mohair is less susceptible to entanglement in scouring and, since it initially contains lower levels of wax than most wools, it can be scoured at a faster rate. Waxes removed in the scouring process are reclaimed from the effluent of scouring plants. Partially refined waxes are used as industrial greases, particularly in applications where water resistance is required. Wool and mohair wax is further refined to produce lanolin which is used in cosmetics and ointments. Traditional scouring of wool and mohair is now considered to be quite wasteful in terms of energy and water usage. Modern technology has drastically reduced the amounts of water and energy required to cleanse the greasy products. An added bonus of this technology is that effluent can be treated more efficiently, thus reducing the cost of wax removal and the cost of making the effluent environmentally acceptable. A combination of high effluent treatment and shipping costs has resulted in the relocation of many scouring plants from the countries where wool and mohair are manufactured to the locations where the fibers are produced. This trend is expected to continue into the 21st century.

Only small amounts of certain types of vegetable material are removed in scouring. Further mechanical processing (carding, gilling, and combing) is necessary to remove the rest. In cases where the vegetable content is deemed too high for mechanical removal alone, the trade resorts to a process known as "carbonizing." In this process, scoured wool or mohair is impregnated with a dilute solution (6%) of sulfuric acid. The impregnated fiber is then squeezed to produce a specific uptake of acid and the fibers are then dried and subjected to temperatures around 105°C for a short time. The combined effect of heat and acid converts the cellulosic, vegetable impurities to carbon. The carbon residue is subsequently crushed and shaken out of the fibrous mass. Neutralizing the fibers in a dilute solution of sodium carbonate followed by a further rinse in a very dilute detergent solution completes the carbonizing process. The fibers are then redried. In addition to removing plant parts and other vegetable material, carbonization can reduce the strength of the wool and mohair and cause the fibers to be more brittle and harsher to the touch. Even under optimum conditions, the process causes the luster of mohair to be diminished.

A number of chemical processes can be carried out in the scouring train once the majority of dirt and grease has been removed. These include bleaching (with bisulfite or hydrogen peroxide), mothproofing, applying bacteriostatic finishes, and dyeing (including application of optical brighteners).

XV. Mechanical Processing

Fibers exiting the dryer after scouring are entangled to varying degrees. Generally, finer fibers are more matted than coarser fibers as a result of the scouring and drying processes. Typically, scoured batches of wool or mohair are blended in various methods using vast machines designed for the purpose. Blending at this stage assures homogeneity of the finished products. Blended fibers are then carded to disentangle the wool or mohair, to remove vegetable material, and produce a fiber web or sliver for further processing. In carding, fibers are essentially separated and individualized by the action of metallic card wires or clothing which are attached to the surface of large and small rotating drums. In the "woolen system" the card web is fed through a condenser in which it is split into continuous, narrow (1.2 cm) strips along its length. False twist is applied to each of the strips which are then wound onto a spool. The resulting product, know as "roving," "roping," or "slubbing," becomes the feed stock for a woolen spinning frame. In this machine, fibers in the roving are drawn out and twisted to produce the desired size (weight per unit length) and type of yarn. Woolen yarns are normally composed of relatively short fibers loosely spun to form a bulky yarn, such as these used in sweaters, tweeds, and blankets. Worsted yarns are composed of longer fibers and are uniform, smooth, lean, and relatively strong. Fabrics composed of worsted yarns such as fine dress fabrics and suitings are typically tightly woven and have extremely smooth surfaces. Worsted yarns require several more processing steps than woolen yarns. In the worsted process, fiber exiting the worsted card is condensed into a sliver. Several card slivers become the feed stock for "gilling" or "pin drafting." In these processes, multiple slivers are drawn down between two sets of rollers while the fiber movement is controlled between rows of pins. The resulting sliver is more uniform (in terms of weight per unit length) and contains fibers that are more parallel in the longitudinal direction than the feedstock. Slivers containing parallelized fibers are mechanically combed to remove short fibers (noils). The rectilinear or French comb predominates in today's worsted industry. However, circular Noble combs are still functioning in some combing plants. The resulting combed sliver is no longer uniform in terms of weight per unit length so it is subjected to at least one but usually several more gilling processes before being wound into balls prior to shipment to a worsted spinning plant. The product after combing and finisher gilling is known in the trade as "top." Top is produced by firms that call themselves topmakers or combers and is sold in the international trade to companies that refer to themselves as worsted spinners. Using pin-drafting, drawing, and/or roving machines, spinning companies attenuate top to a structure referred to as roving. Worsted roving which contains some twist then becomes feedstock for the worsted spinning frame where worsted yarns are finally produced. Ring spinning is by far the most important process used to produce worsted yarns. However, some yarns are still produced by the old flyer and cap spinning systems. New open-end and Repco spinning systems are used to produce specialty yarns. At least one further process after spinning is required to wind the yarn from the small spinning bobbins onto large packages suitable for dyeing, weaving, or knitting. Additionally, individual yarns may be twisted together to form two- (or more) ply yarns using a machine known as a twister.

XVI. Woven and Knitted Fabrics, Carpets, and Felts

Woven fabrics composed of worsted or woolen yarns are constructed on looms by interlacing yarns that intersect each other at right angles. The yarns in the longitudinal direction of the fabric are referred to as "warp" while those that run across the width are called "filling" or "weft." Typically, worsted fabrics are light and durable with individual yarns being visible. Woven worsted fabrics are stronger, smoother, and often more expensive than woolen fabrics. It is not uncommon for a finished woolen fabric to have a completely different appearance than the loom-state product. Finishing for most woven worsted fabrics entails removal of surface fiber ends to create a clear, flat finish. In contrast, finishing of woolen fabrics requires various degrees of felting and usually raising of surface hairs. These processes are described in more detail in the next section.

Weaving is the most widely used fabric construction technique. Many different interlacing patterns (weaves) exist which produce wide variation in appearance and utility. The simplest and most common design is the plain weave. Other common constructions include twill, satin, crepe, and pile (looped and cut) weaves. Many permutations exist within a particular weave type. Specific weaves can be further altered in appearance by changing yarn types and sizes and/or the number of warp and weft threads per unit area.

Most of the designs that are constructed today on complex modern looms were also conceived and constructed by early, primitive weavers. However, evolution of the loom has permitted mass production of woven fabrics of uniform, high quality. In the traditional type of loom, the shuttle carries the filling yarn through the separated warp yarns. Once in place, the filling yarn is pushed into place using a reed. At this point, the positions of the warp yarns are changed and the next weft thread is inserted. The most visible changes that have occurred in loom technology concern the method used to insert the weft thread. To produce faster and quieter looms, the shuttle has been replaced by numerous mechanisms which include the water jet, air jet, and rapier. New methods have also been devised for controlling lifting of the warp threads. These are now so sophisticated that pictures can be woven into cloth to produce tapestry effects. Some of these modern devices are interfaced to computers to facilitate changing and monitoring of the process.

Fabrics composed of wool and mohair are also constructed using the knitting process. In knitting, one or more yarns are directed into a series of interlocking loops. Hand knitting with two or more needles is in common use throughout the world. However, numerous types of knitting machines exist which are capable of producing fabric at faster rates than weaving. As with weaving, numerous designs are used, the more common being the plain, rib, and purl types which are constructed on weft knitting machines. Different knitted fabrics are constructed using the so-called warp knitting technique. Warp knitting is somewhat unique in that it was developed as a machine technique and does not have a hand-constructed counterpart. The first warp knit fabric was produced on a tricot machine. Warp knitting evolved into the fastest method of making cloth out of yarns, the most common construction being the plain tricot jersey. Other types of knits are produced on Raschel warp knitting machines which are capable of handling coarser, spun yarns. A relatively new concept in knitting technology is the so-called knit-weave technique which combines the principles of knitting and weaving to produce a unique type of fabric.

Carpets are constructed using several distinct techniques. These include weaving, tufting, fusion bonding, knitting, needling, and knotting. Some floor coverings are composed of true and needle-punched felts. Whatever the means of construction, carpets, mats, and rugs usually contain the coarser grades of wool and mohair (>34 μm). These fibers are ideal for carpet construction due to their excellent appearance retention, abrasion resistance, resilience, anti-soiling, anti-staining, and anti-static properties. Natural flame resistance also enhances their use in institutional, aircraft, and home carpets where resistance to burning is a prerequisite. As for other textiles, nylon, polyester, acrylic, polypropylene, cotton, and rayon compete with wool and mohair for use in carpets. The approach taken by most manufacturers of wool carpets is to produce a product of very high quality. Thus, the woven Axminster and Wilton carpets made with worsted yarns, tufted carpets composed of woolen or semi-worsted yarns, and the hand-knotted, sculpted carpets made in the Orient, are esthetically and technically among the best carpets produced in the world today.

Wilton and Axminster (names of towns in England) carpets are woven on very specialized looms. Wiltons are produced on Jacquard looms capable of producing loop, cut pile, combination loop and cut pile, level, multilevel, multicolored, or solid colored carpets. Axminster looms are even more versatile and are capable of using an almost unlimited combination of colors and designs. Machine-tufted carpets, being somewhat less expensive to produce, are formed in two distinct operations. First, yarn is needled through a primary backing (composed of polypropylene, for example) to produce the tufts. Then the reverse side of the carpet is coated with a heavy latex, which after baking, holds the tufts permanently in place. Concurrently, a second backing (typically composed of jute) is attached to the primary backing and is also held in place by the latex. Since its introduction, the tufting technique has progressively permitted greater versatility. Today, tufted carpets can be constructed with cut or uncut pile (or combination effects), level or multilevel, solid or multicolored. Printing of carpets has added a further dimension to the production of color effects. Tufted carpets can be piece dyed immediately after tufting, before application of the latex. The technology (PTO) also exists to dye wool and mohair carpets continuously. Differential shades can be obtained by using yarn mixtures composed of regular and shrinkproofed wool, for example. Tufted carpets usually require brief finishing processes (steaming, brushing, and shearing, for example) to further enhance their appearance. Wool and mohair carpets constructed using other technologies represent smaller proportions of the overall carpet market. However, some of the most beautiful (and expensive) carpets constructed today are produced by artisans under relatively primitive conditions and many of these products are purchased as investment items by collectors. Being composed of wool and mohair, floorcoverings are susceptible to insect (clothes-moth larva, for example) damage and must be treated to avoid this problem.

Wool felt is arguably the world's oldest textile structure. Felt is defined (by ASTM) as a textile structure characterized by interlocking and consolidation of its constituent fibers achieved by the interaction of a suitable combination of mechanical energy, chemical action, moisture, and heat but without the use of weaving, knitting, stitching, thermal bonding, or adhesives. As the name implies, part-wool felts are composed of wool mixed with one or more synthetic, cellulosic, or other animal fiber. The combined actions of compression, heat, and moisture are used to manufacture felts starting with carded batts of fibers. The felting propensity of wool depends upon its surface structure. If the fiber scales are removed or covered, wool will not felt. Production of felts is achieved in hardening, felting, and milling machinery. Felts are produced in a broad range of thicknesses and densities. Felts from 1 to 25 mm in thickness are produced in roll form. Thicker felts (up to 76 mm) are supplied in sheets. A broad range of felt densities is available from soft (0.2 g/cm^3) to extra hard (0.7 g/cm^3). Felts are used in a very wide range of applications which are still expanding. To produce this wide range of felts, many different grades of wool (19–32 μm) and other fibers are used in the manufacturing process. The range of fiber length used is relatively narrow (2.5–5 cm). Selection of the correct wool for a particular end-use relies heavily on the skill and experience of the feltmaker. Differences in the origin, average fiber diameter, crimp, and degree of weathering can produce major differences in felting behavior.

A relatively recent innovation has been the introduction of felted yarns. The bulk of this production goes into carpets, but significant production has been used in upholstery, craft, and hand knitting to manufacture products with unique performance and appearance characteristics.

Feltlike products are also produced using weaving, knitting, stitching, bonding, and needle-punching techniques. Often, dissection is required to establish how a particular product was manufactured.

XVII. Wet Processing and Finishing

In the broadest sense, the term "finishing" refers to any process carried out on loom- or knitting machine-state fabric during its conversion into finished fabric. Some wet processes applied to fibers in loose-stock, sliver, or yarn form have marked effects on the finished fabric (e.g., dyeing) and are referred to in this section. Important components of fabric quality that are influenced in finishing include: color, cover, crease resistance, dimensional stability, drape, ease of fabrication, easy care properties, elasticity, handle, surface smoothness, and luster.

Finishing of wool and mohair fabrics usually involves at least three distinct objectives. First, the fabric is cleansed. Second, a specific finish is developed, and third, specialized textures are created. Finishing is divided into two broad categories; wet finishing and dry finishing. Dry finishing includes the drying process itself and wet finishing is typically initiated with scouring (not to be confused with scouring of the raw materials to remove grease, suint, and dirt).

When performing any wet treatment on wool or mohair, the fabrics may be processed in open width or rope form. Washing in open width is best suited to worsteds and other fabrics where a clear finish is required. When fabrics are processed in rope form, special precautions and care are taken to ensure that the positions of creases are changed often in order to avoid permanent marking of the fabric. This is very important during fabric dyeing.

Scouring removes a variety of nonfibrous materials that have been introduced inadvertently or for various reasons. These include spinning additives, warp sizes and lubricants, miscellaneous oil stains, dust, and dirt. Fabrics are scoured in open width and in rope form, the form and type of machine used having a major influence on the final fabric properties. Scouring also results in relaxation of tensions introduced during the manufacturing processes. All this is achieved by immersing and working the fabrics in hot, soft (or softened) water containing adequate soap, soda ash, and/or synthetic detergents for a specific length of time. The time, temperature, and concentrations of emulsifying agents are dependent upon type of goods, levels of impurities, and type of scouring machine. Rinsing follows scouring to minimize the concentration of residual chemicals.

A large proportion (~99%) of wool and mohair fabrics are finished and dyed in their natural color without bleaching. However, when a bright white or a white base for pastel shades is required, bleaching becomes a necessity. The two main agents used to bleach wool are sulfur dioxide (reductive bleach) and hydrogen peroxide (oxidative bleach). Solutions of hypochlorites, so commonly used in the home to bleach cellulosics, cannot be used because they cause protein fibers to yellow and degrade. Traditionally, sulfur dioxide obtained by burning sulfur was used to treat damp fabrics overnight in a sealed container or room (stoving). The process is quite slow and the whiteness obtained is not always permanent. A yellow color develops during the lifetime of the white textile presumably due to reoxidation of the reduced pigments. Many other means have been devised to treat wool with solutions of sulfurous acid. Wool can be bleached with hydrogen peroxide at several stages of processing including loose stock, sliver, yarn, or in fabric form. Acid and mildly alkaline conditions are used to obtain the desired degree of whiteness.

Fabrics containing wool and wool/mohair blends are subjected to milling (or fulling) in order to be consolidated in both warp and weft (length and width in the case of knits) directions and to develop a fabric surface that is felted to the desired degree. Milling and scouring are often combined. As discussed previously, the ability of wool to felt is a direct consequence of its elasticity and scale structure. Two factors, moisture and compressive deformation followed by relaxation, must be present to produce felting in wool. Industrially, felting is achieved in the milling process which involves squeezing the fabric in rope form between high-pressure rollers and then into a spout, thus compressing the fabric first in two dimensions (width and thickness) followed by compression in the length direction. Milling is achieved in mildly alkaline or strongly acidic conditions in the presence of milling lubricants and detergents (or soap).

The purpose of carbonizing fabrics composed of wool and mohair is to remove vegetable matter such as burrs, seed, cotton, rayon, or jute. The principle is identical to that described for scoured fibers. Fabrics are impregnated with dilute sulfuric acid, then dried and baked (~140°C) for a short while. After baking, the fragile dehydrocellulose is removed mechanically by first crushing and then beating the cloth. Residual acid is removed by neutralizing with dilute alkali followed by copious rinsing. Specialized acidizing, neutralizing, and drying equipment is used to carbonize fabrics.

Raising is a dry finishing process for modifying the appearance and softening the handle of fabrics by increasing the number and length of surface fibers. One or both sides of fabric can be raised as in the production of blankets, fleecy fabrics, and velours. Since wool and mohair are most pliable when damp, fabrics are usually raised in a wet condition. Concentration of raising assistants, type of machinery, machine settings, and duration of process all influence the final result. A similar process can be performed on yarns to obtain brushed yarns. This is particularly common for straight and looped mohair yarns spun for the sweater trade. Traditionally, woolen fabrics were raised using natural teazles. Except for special qualities of fabric, teazles have been replaced by wire clothing in double-action raising machines, for example. Brushing and napping machines are used to obtain similar effects but to lesser degrees.

Tentering involves fastening the two edges of fabric using clips or pins to a parallel set of chains and stretching the fabric to the desired (i.e., designed) width. Relaxation in the length direction can be achieved by overfeeding the fabric onto the chains. While the fabric is held to width it is dried in the tenter oven in a continuous process. Since temperatures of 110–140°C are typical, great care is used not to overdry or singe the fabric. Mohair is particularly susceptible to overdrying, with yellowing and loss of luster being the highly visible results.

The objectives of shearing depend upon the type of fabric being considered. When a clear finish is required, shearing is used to completely remove all surface fibers (i.e., as for pool table cloth). However, shearing is also used to control the height of the fiber ends above the surface of raised fabrics (i.e., as in melton type fabrics). Shearing machinery typically consists of several sets of brushes, a shearing bed, and the shearing unit itself which has a fixed ledger blade and a rapidly rotating shearing cylinder with 14–20 helical blades.

Pressing of fabrics is required to improve the appearance and luster. Pressing also affects the handle of fabrics. Pressing is achieved through joint application of heat and pressure in the presence of moisture. Traditionally, hydraulic presses in which the fabric was pressed between smooth layers of heavy cardboard ("papers") were used in batch processes throughout the world. Modern mills are more likely to use continuous paper presses and rotary presses for higher productivity. Unfortunately, the effects obtained by pressing are not usually permanent and decatising is necessary to stabilize the luster, handle, and general appearance achieved up to this stage of finishing. Decatising, which also improves the crease resistance of wool and mohair fabrics, is achieved by winding fabric under controlled open width and tension onto a perforated decatising roller. Layers of fabrics may be separated by fabrics composed of cotton or cotton/polyester. Once on the roller, the fabric is exposed to the action of heat and water. The degree of setting obtained in the fabric is dependent upon the length of the heating period, the moisture content and temperatures of the fabric, and the cooling period on the roller. Several types of decatising machinery are in common use in the wool finishing industry. Wet decatising (boiling and crabbing) machines utilize hot water and steam. Dry decatising (autoclave and luster decatising machines) use alternating steam and vacuum cycles to apply successive hot and cold treatments resulting in high degrees of fabric set and stability. Modern machines are available to perform the decatising process continuously.

A typical finishing sequence for yarn-dyed, fancy worsted menswear suiting might include the following steps: inspect, burl (de-knot), and mend; scour and mill in rope form, crab, cool overnight on the beam; hydroextract, tenter, and dry; steam and brush reverse side; shear, once on reverse side, twice on face; rotary press; decatise for luster, final inspection.

Wool and mohair are dyed in all of the following forms: loose stock, sliver, yarn (in hanks or packages), fabrics, and garments. Specialized machinery exists for dyeing in each of these forms and in the case of fabrics, in open width and rope form, as well as batch and continuous. Discussion of these machines is beyond the scope of this article. Protein fibers can be dyed with basic, acid, direct, mordant, vat, and reactive dye classes. New developments in dyeing and wet finishing are being influenced primarily by environmental rather than cost-efficiency considerations. Thus, there is a trend to scour and dye in shorter liquor to goods ratios and to replace chlorination in shrink resist finishes with more acceptable chemical reactions. Similarly, concerns about discharge of heavy metals will result in reduced use of chrome dyeing.

Printing is another method of applying color to wool and mohair but only about 1.5% of the total world Merino production and very little mohair is printed (this compares to about 40% for cotton). Sliver and fabrics composed of wool or mohair can be printed by a variety of methods. Usually, fabrics are pretreated using an alkaline scour, crabbing, desizing, or chlorinating to render the surface more hydrophilic. Traditional print–dry–steam–develop methods of screen printing are used to achieve excellent color yields and clarity. Discharge, resist, and sublimination transfer printing have also been applied to wool fabrics.

Chlorination/resin application treatments are important for producing fully machine-washable wool textiles. These processes are typically carried out continuously with the wool in top form, although fabrics and garments can be treated. The resin employed most commonly is a water soluble, cationic polyamide–epichlorhydrin polymer (Hercosett 125). The combined effect of chlorination followed by resin treatment is to eliminate the differential frictional effect by partial destruction and coating of the fiber scales. More recently, polyurethane, silicone-based polymers, plasma, and potassium tertiary butoxide treatments have been demonstrated to produce effective shrink resistance of wool fabrics.

Wool and mohair fabrics are protected against damage by clothes-moth larvae and other insects. Numerous organic compounds have been used to make the fibers either unpalatable or poisonous to the moth grubs. The first water-soluble product commercially applied to wool for this purpose was Eulan N followed later by Mitin FF. Both of these products are chlorinated aromatics. The last important chlorphenylid-based products to be developed (Eulan WA New/U33 and Mitin LP) are no longer available. In the late 1970s, synthetic pyrethroids were developed for mothproofing. Permethrin soon became the most popular product but it is now being banned in several European countries following the realization that it is very toxic to aquatic organisms. Mitin LF is still available. Pyrethroids with lower toxicity (e.g., cycloprothrin) are likely to be used in the future. Still, the most effective way to eliminate moth damage altogether is to make the textile inaccessible to moths. Thus, wool and mohair garments should be stored in polyethylene bags or wooden chests constructed for the purpose. Of course, this is not practical for protecting upholstery, wall, or floor coverings in which case chemicals must be used. Following the realization that many respiratory problems in humans are caused by the debris left by dust mites, mite repellents are now being formulated for application to wool and mohair textiles.

With respect to flammability, wool and mohair are regarded as safe fibers. Animal fibers ignite when subject to a sufficiently powerful heat source. However, they usually do not support combustion. When the heat source is removed, wool and mohair continue to burn and smolder only for a short time. Natural protein fibers have a high ignition temperature, a high limiting oxygen index, a low heat of combustion, and a low flame temperature compared to other common textile fibers. In addition, wool and mohair do not melt and drip when ignited, unlike many synthetic fibers. However, some end-uses, e.g., textile furnishing in aircraft, require a higher degree of flame resistance than that which is naturally present. Consequently, flame-resistant finishes were developed specifically for fabrics composed of wool, mohair, and their blends with cotton and synthetic fibers. Nonpermanent finishes used solutions of borax and boric acid which had to be replaced after the fabrics were cleaned. One of the early permanent finishes was based on tetra-kis hydroxymethyl phosphonium chloride bound in a polymer produced by the reaction of urea with melamine formaldehyde. This process was expensive and was superseded by simpler and less expensive techniques based on complexes of titanium or zirconium with fluoride, citrates, or other carboxylic or hydroxy-carboxylic acids. These are applied by a variety of methods to wool and wool-rich blends. More recently, an advance in flame-retarding wool has been achieved by combining the established Zirpro process and tetrabromophthallic acid. This treatment produces very short after-flaring times in wool fabrics and provides high levels of durability to machine washing.

XVIII. End-Uses of Wool and Mohair

The suitability of wool and mohair for specific end-uses is determined primarily by average fiber diameter and length. Ranges of fiber diameter used in the main wool and mohair product categories are shown in Figs. 8, 9, and 10. The shaded areas indicate the relatively narrow range from which the bulk of products are composed. Table VII shows consumption of virgin wool in six major categories. Womenswear (outerwear, dresses, skirts, suits, trousers, coats, and jackets), other apparel, and carpets (woven and tufted) each compose 19% of total wool consumption followed in decreasing order by menswear (outerwear, suits, trousers, jackets, and coats), knitwear (adults,' men's sweaters, and women's sweaters), and other interior textiles. Generally, grades of wool used in underwear and one segment of knitwear are finer than those required for women's woven outerwear.

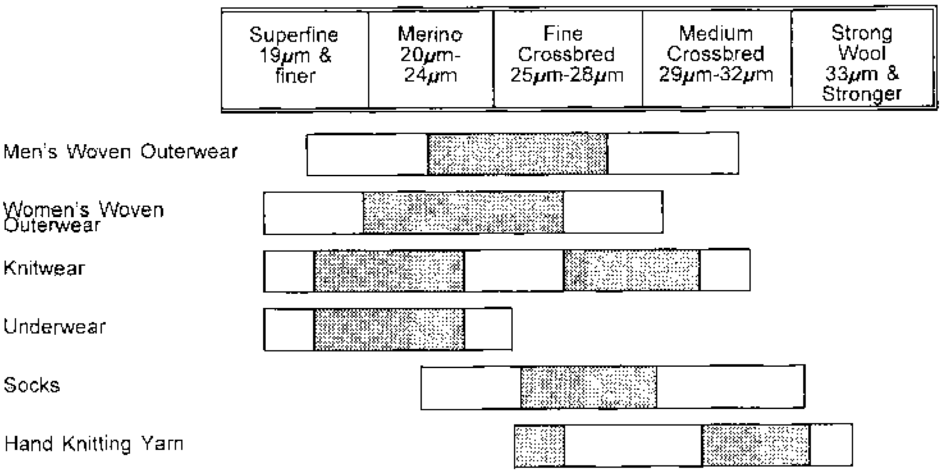

FIGURE 8 Wool diameter ranges for apparel products. [*Source:* International Wool Secretariat.]

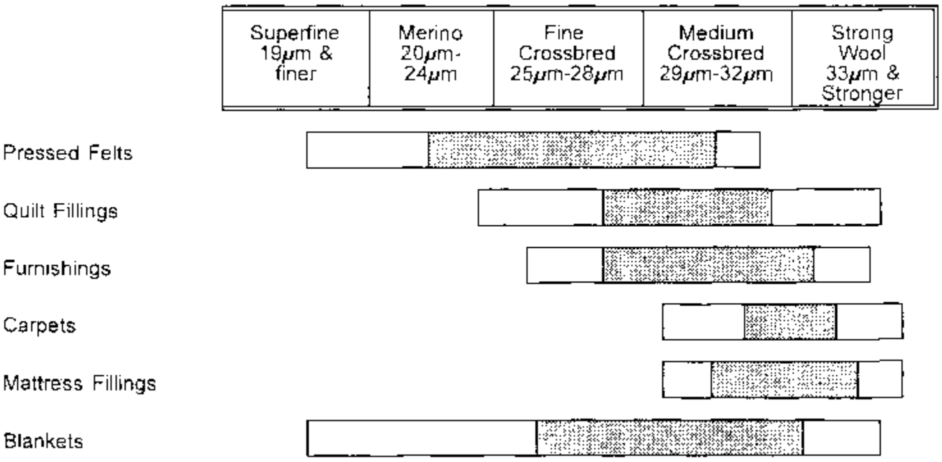

FIGURE 9 Wool diameter ranges for nonapparel products. [*Source:* International Wool Secretariat.]

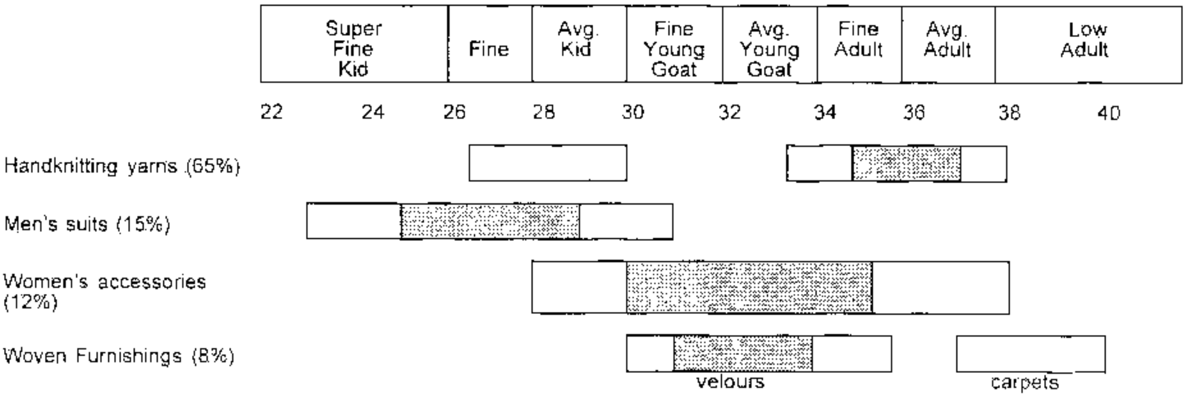

FIGURE 10 Mohair diameter ranges for major products. [*Source:* Mohair Council of America and F. Oglesby Wool and Mohair, Inc.]

TABLE VII
Consumption of Virgin Wool (%)

Apparel products		Nonapparel products	
Menswear	17	Carpets	19
Womenswear	19	Other interior textiles	10
Knitwear	16		
Other apparel	19		
Total	71	Total	29

Source: International Wool Secretariat.

Women's outerwear tends to be manufactured with finer fibers than men's outerwear and socks. The bulk of handknitting yarns are composed of even coarser fibers. Except for some blankets and felts, most nonapparel wool products are fabricated with coarser wools than apparel products.

Wool pressed felts have surpassed all other forms of textile in the number and diversity of their application. Industrially, felts are used for sealing, lubricating, wiping, filtering, polishing, and insulation against vibration. Superfine felts are used for display purposes, particularly exhibition and shop window fittings, soft toys, and in the hat trade. Thicker felts are used for saddle blankets and inner soles for boots, shoes, and waders. Use of felt in clothing has been quite small and dormant in recent times. Although wool felts have been used in floor coverings and furnishings, current use is at a low level. Versatility of felt, the resurgence of interest in natural products, and a new generation of artistic designers who are interested in working with wool felts, are all expected to result in greater acceptance and use of wool felts in the future.

Historically, mohair was used in textiles that were required to be highly durable. Thus, the stereotypical mohair product was a heavyweight, upholstery pile fabric commonly used in public transportation vehicles. Changes over time have resulted in mohair becoming regarded as a luxury fashion fiber. Consequently its use in bus and train upholstery has declined while uses in luxury items have increased. Major enduses of mohair are listed in Fig. 10. In blends with wool, finer grades of mohair are used to produce lightweight (tropical) men's suitings. Since mohair has the capability of being dyed to very bright shades while retaining its natural luster, these attributes are used to produce attractive dress materials, shawls, stoles, plushes, astrakhans, and various types of womenswear coatings composed typically of velour fabrics but also novelty fabrics containing bouclés and worsted yarns. Mohair is also used to produce smooth, high quality linings for suits, curtains, drapes, and table coverings. A small amount of mohair is used to produce highly resilient carpets, rugs, and paint rollers.

The major use for mohair is in hand-knitting yarns in which the natural luster and brightness of mohair combined with its smooth handle, warmth, and tendency to resist dirt, creasing, and felting provide distinct advantages over synthetic fibers and even wool. The bulk of these yarns are knitted into sweaters and other ladieswear accessories. Brushed yarns and fabrics composed of adult mohair and mohair-rich blends often dominate the sweater market when it becomes fashionable.

XIX. Sheepskins

After a sheep is killed for its meat, the skin is removed at the slaughterhouse. All adhering fat and muscle tissue is removed to avoid problems in further processing. Wool may be removed from skins by fellmongering. In this process, fiber removal is achieved through bacterial action ("sweating"), or with the assistance of a depilatory agent ("painting") such as sodium sulfide. Both reactions result in slipe wool (unscoured) and pelts (dewooled skin). Scoured slipe wool is referred to as skin wool by the trade. Pelts are normally pickled in a solution containing sulfuric acid, sodium chloride, and a fungicide. Subsequently, they can be split, degreased, and eventually tanned using one of several methods, e.g., vegetable, chrome, oil, or formaldehyde. However, not all skins are handled in this manner. Soon after removal, skins can be temporarily preserved to permit export or shipping to other locations. This is achieved by drying (air or controlled) or salting. This latter process is usually achieved in a drum which is rotated to distribute sodium chloride (and other chemicals) throughout the "green" skins. Many skins are tanned with the wool intact. These woolskins are used to produce sheepskin goods.

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World Hunger and Food Security

JOHN W. MELLOR, *John Mellor Associates, Inc.*

Glossary

Developed countries Defined geographically as the countries of North America, Europe, East Asia, Australia, and a few other areas in which agriculture is highly productive but small compared to nonagriculture and incomes provide a diverse and high level of consumption

Developing countries Defined geographically as the countries of Asia, Africa, Latin America, and various islands, dominated by agriculture as a source of income and employment and in which incomes for the bulk of the population are inadequate to provide a modern level of living

Food security Assurance of adequate food for a healthy and active life

Hunger Insufficient food intake to allow an active and healthy life

Market prices Prices determined by supply and demand in freely functioning markets

Safety net Legislated and effectively administered minimum quantity of goods and services, particularly of food, made available to ensure a minimum level of living for the poor

Food security is a state in which all people are ensured adequate food for a healthy and active life. The developed countries have largely achieved food security. The bulk of the countries in Africa, Asia, and Latin America have not. Market processes place the bulk of adjustments to a decline in the food supply on the poor who are consequently food insecure. Thus, in food insecure countries governments normally intervene in times of food shortage to protect the poor. Food security is achieved by a complex process of agricultural development in which the bulk of the rural people participate. Technological improvement of crop varieties (usually in combination with increased use of purchased inputs such as chemical fertilizers) is important to achieving food security, as is massive investment in roads and education. Concurrent programs for health and family planning reduce population growth rates and further enchance the per capita availability of food and other elements of improved well-being. The scientifically advanced and wealthy countries can be immensely helpful in assisting the transition of poor countries to a state of food security.

I. Introduction

The agricultural and industrial revolutions of the 18th century made it possible for nations to sufficiently improve their material well-being to ensure their people a healthy diet for an active life. Greatly increased wealth, and the participation of the entire population in producing and consuming that wealth, provided the economic margin for food security. It did so in the face of vagaries of weather, which continued to cause large fluctuations in local food production.

By the mid-point of this century, food security for the total populations had been largely achieved by the well-to-do developed countries. Now it is only destruction of economies by man-made war and civil unrest, not natural phenomena, that can bring inadequate food intake and famine to substantial numbers of the people in those nations. However, food security as the basic condition of a fair and just society still has not been achieved by countries containing a majority of mankind. Bringing food security to all is the achievable challenge of our times.

Fifty years ago, the bulk of humanity, including essentially all the people of Africa and Asia, excluding Japan, lived in a colonial regime. Even the bulk of Latin America was in a strongly dependent circumstance. Under colonialism, the conditions for gross food insecurity and for periodic famine were endemic. Major colonial powers, such as the British, developed intricate famine codes delineating the bureaucratic procedures for ameliorating the effects of famine. But the sheer existence of those codes indicates that famine was the order of the day. Famine was inevitable given the low incomes and lack of participation in development of the bulk of the population.

World War II brought the beginning of the end of colonialism, an end which came rapidly through much of Asia, and more slowly in Africa. Concurrently, those countries of Asia, Africa, and Latin America, which had not been colonies, moved to a status of much less dependence.

Coincident with the departure of colonialism, we find that famines, the most virulent manifestation of food insecurity, declined greatly in incidence and changed radically in causal force. Throughout human history, inclement weather has been a primary cause of famine. Large numbers of poor people obtaining barely sufficient food in normal weather find a lethal insufficiency when a sequence of bad years occurs.

The mechanism by which unfavorable weather caused famine varied from person to person. In some cases, it was simply a lack of production from one's own land. Lack of income and lack of food were coterminous. In other cases, decline in agricultural output directly reduced the employment and income derived by the landless from harvesting and other farm production activities. It also reduced the spending of land-owning people with consequent further reduction in employment in rural nonagricultural goods and service activities. The reduced employment and incomes of the poor, caused by lower agricultural production, would in turn lead to the contradiction of starvation concurrent with apparently adequate supplies of food.

In the postcolonial period, famines have indeed occurred, although generally at lesser intervals and with lesser severity than in the past. Postcolonial period famines have been caused, in general, not by the weather but by civil strife that not only disrupts transport of food from favored areas to nonfavored areas, often by intent, but which also stands in the way of information transmittal and political mobilization to support the famine-hit areas. The massive famine in China, following the "great leap forward" of the late 1950s, was somewhat different than other modern famines. China's brutal central control of the economy and allocation of labor caused massive dislocation of food production and its distribution and control of communication hid the size of the famine from the outside world.

While it is true that modern communication and transportation and the mobilization of assistance from the high-income developed countries has virtually eliminated famine from open, peaceful countries; chronic food insecurity continues in massive proportions, through good years and bad. As countries bring an end to chronic food insecurity, they will have sufficient national income to ensure themselves against the transitory food insecurity of bad crop years.

We have described the circumstance of decolonization, of building new political and economic systems, as a time-consuming and painful process, which lays the groundwork for accelerated economic growth and the achievement of food security for all. A few countries completed those foundation-laying tasks rather quickly and have surged into middle-income status, such that the thought of famine or even of food insecurity for even small elements of their population is unthinkable. Taiwan is the striking example, but we also find Malaysia and Thailand moving quickly into that status.

It is in the next 50 years that we may expect to see the foundation-laying stage passed and countries one after another throughout Asia, and then increasingly in Africa, moving into the stage of accelerated economic growth, rising incomes, and the achievement of food security.

This article first describes the current state of food insecurity in the world, delineates a conceptual framework for processes to ensure food security, and presents programs for dealing with transitory food insecurity, as well as the basic processes for improving or removing chronic food insecurity. The article closes with discussion of the state of food security expected in the 21st century and the broad policy needs to ensure an end to food insecurity.

II. The Present Status of Food Security

Food security is seen by virtually all development oriented organizations as a major affliction. Most institutions, e.g., the World Bank, The Food and Agriculture Organization of the United Nations, the International Fund for Agricultural Development, define food security as a circumstance in which all people at all times have sufficient food to lead healthy and active lives. Such a broad, but powerful definition, conveniently divides itself into chronic aspects of food security and transitory aspects.

Chronic food insecurity describes the situation of those people who, at least for significant periods of each year are food insecure on a day-to-day basis. Such food insecurity manifests itself in the significant stunting of children. For example, the children of the poor in poor countries, due to food insecurity, are typically several inches shorter than the children of the urban middles classes in the same country at the same age. People who in many, or even most, years are food secure, but who become food insecure in specific years of unusually unfavorable weather or civil strife, are said to be victims of transitory food insecurity.

A. The Numbers and Geographic Locations of the Food Insecure

In round numbers, about 700 million people are in a state of chronic food insecurity in this the last decade of the 20th century. Food insecurity is endemic in South Asia where on the order of one-third to one-half of the population are in a food insecure state and comprise roughly half of the food insecure of the world (Table I). About one-fifth of the world's food insecure are in Africa, where the proportion of the population in food insecurity is similar to that of South Asia. However, food insecurity either has been declining or is in an incipient state of decline in South Asia, while it has been increasing in Africa. Thus, within a decade there may well be more people in chronic food insecurity in Africa than in Asia. Another 10% of the food insecure are in China, primarily in the low production potential areas. The proportion of the total population in a food insecure state is about half that of South Asia. The remaining fifth of the food insecure are largely scattered in Latin America, North Africa, and the Middle East.

In addition to the 700 million people in chronic food insecurity, an additional 300 million people are close enough to the margin of chronic food insecurity that fluctuations in weather cause them to move back and forth across that line. Thus, we may speak of the total number of people in food insecurity as about one billion.

TABLE I

Geographic Distribution of Poverty and Consequent Food Insecurity, 1990[a]

				Agricultural potential	
Region	Total	Urban	Rural	High	Low
		(millions of people)			
Africa	137	14	123	62(50)	61(50)
South Asia	350	70	280	140(50)	140(75)
East Asia	31	5	26	6(25)	20(75)
Latin America	72	29	43	11(25)	32(75)
Near East	34	10	24	8(33)	16(67)
China	76	0[b]	76	25(33)	51(67)
Total	700	128	572	252	320

Source: Mellor, J. W. (1990). Ending hunger: An implementable program for self-reliant growth. *In* "The World Food Crisis: Food Security in Comparative Perspective" (J. I. Hans Bakker, ed.). Canadian Scholars Press, Canada.

[a] The distribution by rural and urban classification is based on a survey of country poverty studies. All poverty in China grouped under rural poverty. There is little evidence of malnutrition in urban areas. The classification into agricultural potential is based on unpublished work by Sumiter Broca at IFPRI.

[b] Assumed to zero, a reasonable assumption when migration is regulated.

[c] Numbers in parentheses are percentage of rural population.

With such massive dimensions to food insecurity, it seems unlikely that the more well-to-do people in the relatively prosperous countries would, year-after-year, provide the transfer payments to lift so many people to food security on a long-term basis. The obverse is that the solution to the food insecurity problem must come from bringing the mass of the food insecure into the development process. Incomes must be raised through broad processes of development, based on agricultural growth and the stimulus to nonagricultural growth that comes from rising farm incomes. The key to those processes is improved agricultural technology arising from modern agricultural research systems.

The centrality of broad participation in economic growth to food security is explicitly recognized by the World Bank, the Food and Agricultural Organization of the United Nations, and the International Fund for Agricultural Development. Several of the bilateral foreign assistance agencies have also done position papers that recognize this relationship between growth and food security. With that perception, the effort to reduce food insecurity largely takes the form of broad development efforts rather than specific food security projects. [*See* INTERNATIONAL AGRICULTURAL RESEARCH.]

It should be clear that food insecurity and poverty are two sides of the same coin. People who are not poor allocate their income in such a manner as to be food secure. They may, of course, not do so very efficiently, and they may suffer some malnutrition from a poor allocation of their food budget. But they do have adequate calories for an active and healthy life. The food insecure are those who have inadequate income to command adequate quantities of food.

There has been some controversy as to whether food insecurity is a problem of inadequate supplies of food or inadequate income for commanding the food. As we will see later, this is an unproductive and diverting argument. Of course, the poor, being poor, do not have the purchasing power to obtain adequate food. However, it is the processes of increasing agricultural production and various direct and indirect effects of increased agricultural production which provide the increased incomes and purchasing power that lift the poor to food security.

B. The Rural Nature of Food Insecurity

The poor are primarily in rural areas. In Africa, roughly 90% of those who are so poor as to be food insecure are located in rural areas; in Asia, the proportion is about 80%; and in Latin America, with much higher incomes and more differentiated economies, the proportion of the poor in rural areas is much lower but still on the order of 60% (Table I). Many of the urban food insecure have fled the countryside because of endemic food insecurity. Thus, the basic solution to food insecurity lies in the rural areas of the poor countries. [*See* RURAL DEVELOPMENT, INTERNATIONAL.]

The distribution of the poor within rural areas relates to the level of development and instructs us as to the strategy for providing food security. In the very poorest countries, the poor are located with greater density in the rural areas with substantial agricultural production potential (Table I). Examples are the densely populated, but agriculturally rich areas of the Gangetic and Brahmaputra basins of South Asia, the volcanic soils of Java, and the upland farming areas of western Kenya. In each case, both the overall rural population density and the density of the food insecure poor are very high.

Reducing poverty and increasing food security is a straightforward process in such agricultural, technology-responsive areas. Not only does accelerated growth in agricultural production create many more jobs directly in agricultural production, but also the expenditure of higher agricultural incomes creates substantial growth in employment, in the expanding provision of nonagricultural goods and services. The high rural population densities reduce the cost per capita of provision of the physical infrastructure of all-weather roads, electrification, and telephones which are so essential to rapid growth in rural nonagricultural employment. Thus, we find that in middle-income developing countries, the poor are virtually not to be found in the good agricultural areas and instead are found largely concentrated in the poorer agricultural areas. In those countries, development has lifted people in the more productive areas out of the absolute poverty which brings food insecurity. Thus, in higher income Thailand, there is essentially no poverty or food insecurity on the rich soils of the Central Plain. Such poverty is largely concentrated in the much poorer areas of the Northeast. In contrast in the poor countries of India and Bangladesh, we find a substantial proportion, perhaps on the order of 60–70%, of the food insecure concentrated in the rich alluvial areas of the major river systems and in the coastal areas.

We can draw a conclusion, which we will expand upon in later sections, that in the poor countries it makes sense to concentrate first on lifting people out of poverty and into food security in the richer agricultural areas. When those easier problems have been solved, one can then move to the more intractable problems of dealing with those on the poorer soil areas.

C. Children and Women

Children, in particular, and to a lesser extent women as well, are disproportionately represented among the absolute poor and the food insecure. The disproportionate representation of women arises partly from the general problem of maintaining adequate incomes in single-family headed homes but also from discrimination against women, particularly as societies modernize and as women are restrained from taking full advantage of the modern institutions such as credit, and purchased inputs, which play such an important role in lifting people out of rural poverty.

Children are disproportionately represented amongst the food insecure because the poor tend to have larger numbers of children than the more well to do and because large numbers of dependents bring greater poverty, at least in the short run. The problem of food insecure children has two faces. First, there is the extraordinary humanitarian problem of small defenseless people facing chronic hunger with its debilitating effect on their physical and mental development. The other face is the creation of a new generation of people who are vulnerable to ill-health, and have not experienced the mental development which should occur with increased schooling.

III. The Conceptual Framework for Increased Food Security

Solution to the massive problem of food insecurity requires a combination of market-oriented development activities, a public safety net involving redistribution of income, and a complex mix of public and individual action. The complexity is simplified by Mellor's Food Security Pyramid, depicted in Fig. 1.

The current dimensions of food security are depicted by the broad base of the pyramid, representing the 750 million people in chronic food deficit and the 300 million who occasionally become food deficit in periods of unfavorable weather or other natural disaster. The aspiration of a food secure future is represented by lateral and vertical contraction of the pyramid to the point of the pyramid at which time food insecurity has been eliminated.

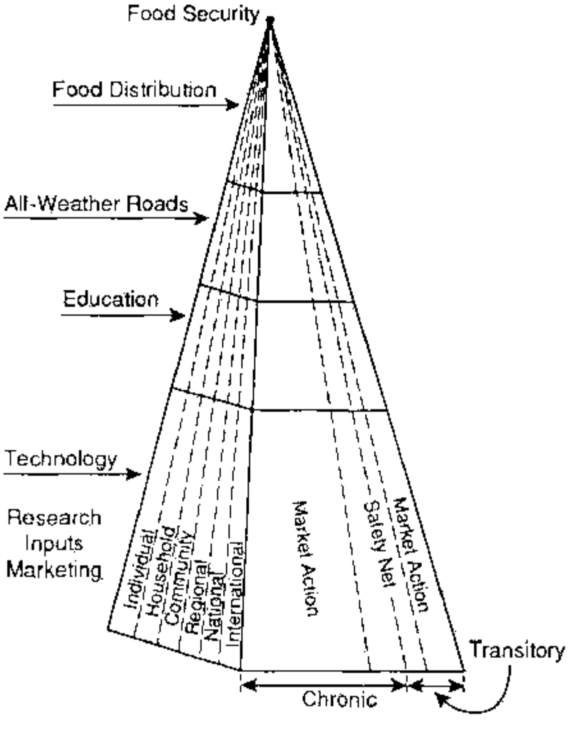

FIGURE 1 Food security pyramid.

The front face of the pyramid depicts, in horizontal bands, the actions to achieve food security. The vertical dimension comprises two segments representing chronic and transitory food insecurity. Each of those is further divided into the components to be treated by accelerated growth achieved through the operation of private enterprise and free markets in cooperation with complementary public activities and the components requiring direct public action to provide a safety net of income transfers. The side faces of the pyramid designate the continuum of action from the international arena through various levels of national organizations, both public and private, reaching the ultimate objective of the family and the individual child, woman and man within the family.

Because of human disability and misfortune, it is unlikely that the ultimate objective of contracting the pyramid to the point of universal food security will be achieved entirely by market processes. Hence, specific public programs will continue to be necessary. But the objective of moving close to that point on the basis of development and growth, supplemented by public income transfers is attainable. The remainder of this article treats the range of approaches needed to achieve that objective.

IV. Actions to Achieve Food Security

The numbers of the food insecure are so large that growth must be the primary instrument of food security. Thus, the bulk of the width of the pyramid, for both chronic and transitory food insecurity, comprises market-oriented growth activities. Those activities are much larger in total than what is depicted on the food security pyramid. The pyramid only includes the specific orientation of those efforts toward food security. Thus, as the pyramid compresses, the size of those activities specifically oriented toward food security may decline, while the general activity increases. Within the context of market-oriented growth, specific government programs will provide income transfers to reduce food insecurity.

Many types of effort contribute to increased food security. Some efforts have a direct effect while others, no less important in their impact, are indirect. Classes of such effort are depicted as horizontal bands on the pyramid with those having the most direct effect near the top of the pyramid and those having the most indirect effect near the base. Each of those activities is pursued through international and national collectivities, as well as by family and individual effort, and so they slice across the pyramid in each direction.

A. Chronic Food Insecurity

1. Markets and Growth

A development strategy that accelerates growth in the agricultural sector is key to radical reduction in poverty and hence in food insecurity. Thus, in India, the five states with the fastest growth rates of the agricultural sector reduced the proportion of the rural population in absolute poverty by over half in the 20-year period, 1963–1983. That was a period marked by similar weather at the beginning and the end of the period and hence, the trend is not biased by differences in weather. The states that did poorly in agricultural growth actually experienced an increase in the proportion of their rural population in poverty. Countries that have done well in agricultural development, such as Indonesia, Thailand, Malaysia, and Taiwan, have all experienced radical decline in absolute poverty and hence in food insecurity in parallel with the agricultural growth.

The food security pyramid draws attention not only to the importance of a broad process of agricultural growth, but also for the need to see that the process plays its role in reducing food insecurity. Thus, each activity needs to be monitored from that point of view. Does the food distribution system work effectively in areas where the poor are concentrated? Is intervention needed to ensure competition, low cost, and wide access? Are all-weather roads introduced in all food insecure areas? Does education include not only basic skills but nutrition education to improve allocation of resources for the poor to achieve food security? Is the agricultural technology system adequately oriented to the crops and livestock important to food security because of their importance in consumption or in generating income for the poor?

2. The Food Distribution System

It is the food distribution system which is, of course, closest and therefore most direct in bringing food security to the poor and innately insecure. An effective food distribution system will be largely operated in the private sector. The scale economies are not large, and the advantages of competition are great.

The primary role of government in the food distribution system is to ensure competition in the private sector. Of course, the better the system of physical infrastructure, education, and technology, the more competitive will be the private sector.

The public sector also has a role in dealing with the problems of market failure and, more important, victimization by the market. The latter is perhaps best made clear by pointing out how the market allocates a reduction in food supplies. It does so through price and the relevant income elasticities of demand. When the supply is reduced due to poor weather or other forces, prices go up. How much they go up is a function of the elasticities which reflect the resistance of a particular income class to reduce their consumption in the face of a decrease in supplies and rising prices.

The resistance of the consumer to reduced food consumption is a function of how high is the income of the consumer. In countries with very substantial populations of poor people, prices only have to rise a small amount in order to bring supply and demand into balance. That is because very poor people spend the bulk of their income on food and so a price increase brings about a drastic reduction in real income and hence a reduction in purchases. We can reflect this in the income elasticities and make relevant calculations.

Those calculations show that in a very poor country where the bottom 20–40% of the population has barely enough income to provide the minimum calories for a healthy active life, with a decrease in national food supply, the lower 20% in the income distribution reduce their food consumption by 10 times as much as do the top 5% of the income distribution. With higher prices the poor simply cannot afford as much food as before. That is, those who are hungry have to reduce consumption greatly, while those who are not hungry reduce their consumption very little when supplies decline. We consider that inequitable and all societies attempt to take action to prevent the working of markets under those circumstances.

Thus, we find in the case of transitory food insecurity, that markets do not meet societies' objectives and there must be interference. That interference, however, may involve simply taking supplies from public stock and putting them on the market to reduce price increases, or using foreign exchange to purchase internationally traded commodities to have the same effect.

3. All-Weather Roads

Without all-weather roads, food security is a function of local food production–consumption balances. Whereas food production in a small region may fluctuate as much as 50% from one year to another, and in virtually all regions is subject to at least 5–10% fluctuation, the total production of food in the world rarely fluctuates as much as 5% from one year to another. Bad weather in one place is balanced by good weather elsewhere. Thus, maintaining stable supplies and prices of food is much easier with an integrated global market. Provision of transport and other infrastructure to fully integrate markets globally is an important form of food security investment. It is also a key element in rural development.

In Asia, typically one-third of the rural population is not served by all-weather roads. In Africa, typically 90% of the rural population is not served by all-weather roads. Building roads in developing countries is a very labor-intensive process and thus road construction provides a further benefit to food security by increasing the purchasing power of the poor. In this context, food aid can be an effective means of increasing both chronic and transitory food security.

4. Education

Although the relation between education and food security is much less direct than for all-weather roads and the food distribution system, it is nevertheless important. Education is a critical element for the relief of chronic food insecurity through its effect on development.

Over time, knowledge which is so essential to progress, becomes more and more complex, requiring higher and higher levels of education. This is particularly true if environmental damage is to be avoided.

Education is also important in dealing with chronic food insecurity in the long run, because of its close relationship to family planning and population control. Thus, including women in education is particularly important. Reinforcing the need for education of women is the increased potential to improve the effect of higher incomes on food consumption and health. At very low incomes the choices for food expenditure are very limited. Rising incomes increase those choices and hence increase the return to education and particularly the education of women.

5. Technology and the Environment

The basis for increased incomes in all economies has been primarily through technological improvement. The way we increase incomes is not by increasing the supply of the factors of production so much as by making those factors of production more effective. Thus, technological change and its corollaries of research, increased input intensity, and improvement of marketing channels are crucial to the development route to increased food security.

Measures to ensure that the poorest and most food insecure benefit from improved technology start with research emphasizing commodities and conditions which are particularly important to the poor. There may also be an emphasis on increasing the productivity of land and capital which the poor have little command of, and with less emphasis on increasing labor productivity through use of more land and capital.

It is notable that improved technology requires capital and will tend to be less accessible to the poor because of the higher cost and greater risks in providing them with credit. Thus, a food security program will emphasize giving the poor access to improved technologies by opening to them the input distribution systems, the marketing systems, and in particular the credit systems.

Modern yield increasing technology has generally had favorable effects on the environment. The most important favorable effect arises from raising productivity of the better land to make it unnecessary for the poor to push out on the extensive margin of food production. The most striking examples of such destructive pushing back of the margins for arable food crop production lie in the humid tropical forests and the semi-arid grasslands. In each case the environmentally sound agriculture is based on perennial crops (grasses in the one case and trees in the other). Poverty pushes the poor to switch to arable, annual crops with consequent exposure of fragile soils to the destruction of sunlight, water, and wind, thereby accelerating their breakdown and erosion.

The higher productivity associated with improved technology also increases the availability of nonfarm jobs through the expenditure of the higher incomes of farmers and makes food less expensive to the poor who move off marginal lands, letting them revert to more appropriate uses, and move to nonfarm jobs. These favorable effects of modern yield increasing technology are rescuing large areas of fragile lands even as agricultural production concentrates on the more robust lands.

The increased intensity of high yield agriculture requires a high level of education of farmers, and extensive public support systems if the environmental advantages are not to be partially nullified by pollution. In poor agriculture, it is degradation of soils through erosion and depletion that represents the major environmental hazard. In high-income countries, it is pollution that moves to the forefront. However, no farmer wants to pollute. Chemicals are applied to benefit plants and those that leach into groundwater or are otherwise environmentally destructive do not benefit anyone. The farmer requires support of soil testing, so he or she applies the amount of chemicals needed, and research to advise on the timing of the application to maximize the effect on crops and minimize the unfavorable effects on the environment. This requires expanded public soil testing, research, and extension as well as the education of farmers. It may also require legislation to enforce needed environmental practices. But, even in the face of these problems of modern agriculture no mistake should be made in preference for the much more destructive systems of poor people facing poverty and population growth on resources that are not meant for arable agriculture and which can be displaced only by modern science and its application.

6. Safety Net and Income Transfers

Each of the slices of the pyramid has scope for special expenditure to ensure access of the poor. Through misfortune, some people will always lack the capability to provide self-sustaining food security to themselves. The extent to which that is the case will form a gradation, which offers scope for programs that range from developmental to redistributive. For example, food distribution programs can provide free food to the poor and destitute; education programs can include school lunch programs which help bring children to school and relieve food insecurity directly; and road-building programs can employ the food insecure and pay them with either food or cash for purchasing food, depending on circumstance.

B. Transitory Food Insecurity

1. Markets and Development

Treatment of even transitory food insecurity can, with adequate planning, have a developmental aspect. The private sector can be facilitated in providing distributional services. Plans can be made to tool up public works projects that build roads and school lunch programs can be enlarged. On-going developmental programs provide the basic administrative structure to respond to short-term emergencies and should be designed to fulfill that purpose.

2. Safety Net and Transfers

Transitory food insecurity also has a clear safety net or distributional aspect. In time of agricultural failure, large-scale distribution of both income and food may be necessary to meet the needs of destitute people.

V. Public Action and the Individual

The ultimate objective of food security lies with the family and the individual within the family. Each of the slices of the pyramid has an international, a national, a local governmental, a private organization, and a family and individual aspect. In each case, the program must be carried through to the individual with emphasis on conforming to the specific needs of individual children, women, and men.

A. International

International programs of food security are important because of the lesser fluctuations in global food production relative to those of small regions. It is expensive to ensure food security through stocks in small regions or nations. Because the weather is highly random, in any one area there can be substantial sequences of good or bad weather, and the consequent size of required food security stocks is immense. However, by the very nature of the randomness of weather, it is unlikely that poor weather will be general, throughout the world, at any one time. Thus, poor weather in one place is balanced by good weather elsewhere. Shipment of food from areas of good crop to areas of poor crop is a less expensive substitute for storage, to convey food from good years to poor years.

Thus, there is much to be said for dealing with the food insecurity problem at the international level with finances rather than stocks. However, poor countries suffer from problems similar to those of poor people—they have difficulty in saving and providing for difficult future circumstances. If poor countries can be guaranteed finances for importing food, they can bid that food away from the richer people who will respond by reducing their livestock consumption and hence the heavy drain of cereals into livestock feed.

In the 1980s, the International Monetary Fund set up the IMF Cereal Facility to fulfill this need. Unfortunately, there was not sufficient understanding of the special nature of food as a commodity, and hence the need for a specialized facility. Consequently the IMF Cereal Facility was substantially integrated with other foreign exchange mechanisms. The result of that and other restrictions was that it was not frequently used, and eventually became redundant. An important and efficient instrument of international contribution to food security was thereby lost.

The World Food Program, as a major international agency, is able to provide physical supplies of food in times of emergency. It also uses food aid to deal with chronic food insecurity, while at the same time furthering the development process, particularly through the Food for Works Program. This program provides food as partial compensation to those who help to build roads. It is notable that a number of bilateral donors of food aid, particularly the United States, use financing for their food aid as a means of dealing with important transitory problems and may be looked upon as part of the international system for food security.

Because of the importance of financing and the fungibility of finances, the World Bank has played an important role in food security. When countries experience sudden financial crisis, the World Bank can emphasize quick dispersing loans which in effect provide ready foreign exchange for importing food under those circumstance.

One of the objectives of the international trade negotiations of the 1990s is to reduce the production of surplus agricultural commodities in the high-income countries. One result will be reduction in the size of food stocks that high-income countries provide to developing countries, through administration of their national policies. That, in turn, will increase the instability of international prices and the supplies of food available on a concessionary basis to poor countries. In that context, increased attention needs to be given to international mechanisms for protecting poor people in poor countries from fluctuations in food availability and supplies.

B. National

National governments are crucial to reducing food insecurity. National stocking policy must ensure supplies until a transitory food insecurity situation is properly diagnosed, orders placed for food abroad, and time provided for the food to arrive. The less developed a country and the poorer its informational and transportation system, the larger those stocks must be. Some countries need as much as a 4-month supply. But for countries with more sophisticated physical and institutional systems for food security, a month or two would be adequate.

Food security requires a national food price policy. That is because it is efficient to turn to international supplies at times of transitory food insecurity. It is defending a price level derived from national policy which provides the operating rules as to when food should be imported, stocks built, and stocks depleted.

And of course, national governments are very important to agricultural development. Because farming is most efficiently carried out on small units, governments play an important role in providing research for improved technology, helping farmers organize various activities and providing physical and institutional infrastructure, including rural roads and schools.

C. Local Government

Local government is the most effective means by which international and national programs are linked to the family and individual. Small areas differ in many respects relevant to food security, such as food habits and the quality of the food distribution system. The more highly developed local government is, the more food security efforts can be fine tuned to the local situation. Nongovernmental organizations also play an important and crucial role in fine tuning of food security programs. They can organize the poor to represent their interests, and they can stand as an intermediary between poor groups and various levels of national and international governments.

D. Family and Individual

The family unit is the final objective of food security. It is noted that sometimes food is inequitably distributed within the family. However, such inequity is almost always a product of poverty. As incomes rise, the inequity of allocations within the family decline.

The family may maintain stocks of both cash for purchasing food and actual physical stocks of grain. However, the poorer the family, the smaller are such stocks. Indeed, it is the hoarding action of the more well-to-do which tightens food supplies in times of scarcity and increases the burden on the poor. Poorly developed information systems and poor infrastructure compound the problem. Thus, food security for the poor in poor countries requires public stocks and the capacity for public intervention in food markets.

VI. Population Growth and per Capita Food Availability

When Japan entered the initial period of accelerated economic growth in the late 19th century, an agricultural growth rate of around 2% per year allowed per capita agricultural output to grow at over 1% per year. That growth rate made an important contribution not only to increasing food security but also to supporting rapid growth of the nonagricultural sector and the eventual transformation of the economy to its current modern, wealthy, industrialized status.

Modern medicine has sharply reduced death rates even among very poor populations. A combination of less radical scientific advance in birth control and more complex social processes has left birth rates at high levels. Thus, population growth rates in modern developing countries are three times the levels in 19th century Japan. Agriculture must grow at some 4% per year to make as large a contribution to achieving food security and to overall economic growth as was achieved in Japan.

Fortunately, the application of modern science, reinforced by the benefits of trade, allows a catching up growth rate of 4% or so in the initially backward agriculture of developing countries. But such rates cannot be maintained indefinitely. Eventually population growth rates must be brought down.

Economic growth itself brings education, change in values regarding investment in education of children, and how early children commence adult work, all of which help reduce birth rates. But general education, integration into the larger society through improved communications, and provision of desired information about birth control speed that process. Knowledge and efficiency are increasing in all the components of birth rate reduction and so each succeeding generation of fast growth countries brings its population growth rates down more rapidly the preceding generation.

However, a few countries in Asia and most countries in Africa are lagging in these processes, are experiencing unprecedented rates of population growth, and must give special attention to the social, economic, and technical processes involved in reducing birth rates. Otherwise an intolerable burden is placed on agricultural growth alone to bring food security. Although economic growth and reduction of birth rates are highly complementary and go hand in hand, it is still notable that a percentage point reduction in the population growth rate is as valuable as a percentage point addition to the agricultural growth rate in eliminating hunger and achieving food security.

VII. Progression and Phases toward Food Security

The global task of universal food security can be achieved by the early decades of the 21st century. To do so will require concerted action and attention. In understanding global progress toward food security, it is useful to define three quite different phases. The phases differ in their central tendency, but represent a continuum of change.

A. Phase I

In Phase I, countries are very poor, the level of per capita production of food is well below that needed for an adequate diet, and the level of effective demand (that is the food which people can afford to buy) is roughly the same as the amount which is produced because producing food is the principal source of income. There is little trade. On the order of half the population is food insecure. Nowadays, population growth in this phase is rapid, increasing the food security and hunger problem, since modern development is not yet occurring and therefore food production is growing very slowly.

B. Phase II

In Phase II, technological improvement occurs at an increasing rate in the agricultural sector, and there begins to be acceleration in the production of food. If the economic processes are working well, the increased incomes from the food production will be substantially spent by the food producers, either to purchase that food itself (that is to retain it on the farm and to consume it) or to purchase relatively labor-intensively produced goods and services from the local community. The latter increases the incomes of the landless and hence their purchasing power for additional food. Because the nonagricultural sector is initially small, we can show mathematically that in the first part of Phase II there will be modest decline in food prices and quite possibly the supply will increase somewhat more rapidly than the effective demand, creating some exportable surplus. It is important that population growth rates begin the decline.

As the development process gets under way, a second part of Phase II emerges with rising real food prices or rising imports of food. The rate of growth of food production will further accelerate and there will be a better working process for increasing incomes in the nonagricultural sector, at first substantially stimulated by growth in agricultural incomes and then growing on the basis of its own income generation. The effect is growth in the effective demand for food which is considerably more rapid than the growth in supply, resulting in rapidly increasing imports. This supply–demand balance is very heavily driven by the rapid increase in the consumption of livestock commodities and hence much of the import of food will be for livestock feed. Again, it is essential that the processes for reducing birth rates be well under way in this phase.

We note this phenomenon particularly markedly in Taiwan, which went from being a modest net exporter of food in the early 1950s to becoming a massive importer of food in the 1970s and subsequently, with livestock feed driving those imports. During that period, the growth rate of the agricultural sector was rapid.

Unfavorable macro-economic policies (e.g., an over-valued exchange rate; allocation of the nations capital to low employment industries in the capital city) may intercept the favorable multipliers from the agricultural sector. The Philippines is an example. For a considerable period in the 1960s, 1970s, and 1980s, the agricultural growth rate was rapid, but growth in nonagricultural employment was slow, the real wage rate declined, and effective demand for food grew less rapidly than the supply. But that is not the normal set of relationships under more favorable macro-policy regimes. In fact the Philippines is the lone example of agricultural growth not driving nonagricultural growth.

We can make some profound statements about food security in the context of these growth phases. Most importantly, the production of food per capita grows rapidly as we move into Phase II . That increases food security by allowing people to consume more per capita than before, and thus they are able to sustain a substantial temporary drop in per capita supplies due to bad weather without reducing their consumption below the earlier levels. At the very least, they have improved their food security.

We note further that as livestock consumption increases, there is a further source of stability in consumption of food by humans. If there is a shortage of food, an increase in grain prices squeezes the margins of livestock producers who will then increase their marketings of livestock. That has two effects: an immediate increase in livestock supplies and hence consumption; and less feed consumption by livestock. Since livestock consume from 3 to 10 calories for each calorie produced, the increase in supplies for human consumption is large.

C. Phase III

In Phase III, institutionalized technological change continues to provide a significant growth rate in food production, but growth in per capita food consumption levels off. People's desire for additional food has been largely satiated and they are food secure. Even though the production growth rate may decline somewhat during this period, it still increases significantly faster than consumption, generating surpluses.

Now, when so much of the Third World is entering Phase II of food security, it is fortunate indeed that we have a substantial proportion of the world's population in Phase III, generating food surpluses. However, the world needs to show more intelligence in seeing that these food supplies effectively facilitate the development of poor countries that provides the long run guarantee of food security.

The major burden on global food supplies will come as massive countries, such as the collectivity in South Asia and China, move clearly into the second part of Phase II of food security. Supply–demand projections for India show that in 10 years of rapid income growth; net imports of cereals will increase to about 10 million tons. Those imports will be primarily in the form of coarse grains, reflecting the rapid growth in livestock consumption and feeding which is just commencing.

The tremendous growth in demand for livestock feed does not occur immediately with the onset of economic growth. The base of livestock consumption is initially small so even a high percentage growth rate still does not have a significant aggregate effect. In addition, livestock feed in early stages of growth comes largely from waste and by-products. However, the supply of those commodities is relatively inelastic. As the base of livestock consumption increases, the by-products supply is soon fully utilized. Then, when the base of livestock consumption is large, by-product feeds are fully utilized, and rapid growth in income continues, explosive growth in the use of cereals for feed is reflected in rapidly increasing imports.

The phases of food security are paralleled by phases of population growth. In the early phase, population growth has traditionally been modest with death rates a little lower than birth rates. As development occurs, the death rates come down sharply, providing explosive increase in population. Modern medicine is pushing this explosive growth in population in Phase II. In the next phase, birth rates begin to decelerate and the decline in death rates slackens, and the two begin to close in, slowing the rate of population growth.

1. Food Security in Phase III

In Phase III, countries return to self-sufficiency or even increase exports of the basic food staples such as wheat and rice that are directly used for human consumption. There may be, depending on the agricultural resource base, substantial import of horticultural commodities and either livestock products or the feed for producing livestock products. Ensuring the certainty of such a high-level diet for high population density, high-income countries requires earning foreign exchange to purchase food from abroad as needed. Supplies of food are produced in sufficiently politically and ecologically, diverse regions that food security is virtually entirely a matter of having the economic strength to be able to export goods in payment for food. With food security ensured by trade policy the concern for domestic agriculture changes from issues of agriculture's role in economic growth and food security to issues of farm incomes, rural life style and indeed the life style of the nation, and environmental concerns including its health and esthetic aspects.

2. Environmental Issues in Phase III

Because food security is assured in Phase III by a combination of domestic production and trade, and because environmental problems have increased by the very nature of development, environmental issues receive a different weight compared to the food insecure phases of development. It becomes economically sound to err on the side of control of pesticides and fertilizer use in order to preserve human health and the groundwater table. In addition, with diets satiated, consumption rising little or not at all, and technology increasing the productivity of agricultural resources it makes economic sense to take some of those benefits by withdrawing resources from agricultural in favor of environmentally sound practices. In some countries, that may well proceed to the point of requiring increased imports of food. The latter can be financed because of the high overall level of productivity in the economy.

VIII. Policy Requisites for Global Food Security

The vision presented of achieving virtually universal food security over the next few decades requires sensible policy. That policy has six elements.

First, all developing countries must pursue vigorous technological change in their agricultural sectors through research and its application and bring all people into an exchange economy through good rural infrastructure and universal education at least through the secondary school level. Foreign technical and financial assistance can greatly speed those processes.

Second, technical, social, and economic policies need to be pursued to bring down high rates of population growth.

Third, an international mechanism is needed to help the poorer countries finance food flows to ensure against transitory food insecurity.

Fourth, open-trading regimes are essential. They facilitate increased incomes to developing countries as they specialize in commodities to which their resources are best suited.

Fifth, as we approach global food security, we can attach increased weight to approaches to agriculture which may increase the cost of production but preserve and enhance the physical and esthetic qualities of the environment.

Sixth, as each nation approaches a state of food security it must pursue policies which maintain flexibility to adjust agriculture to stagnating demand in the face of continued technological improvement.

The greatest dangers to the hope of universal food security are (1) that the developing countries will not give the centrality to agricultural development that is essential to broadly participatory economic development, and (2) that the developed countries will not use their food surpluses to foster the short-term transfers and the long-term increase in rural infrastructure and education that can be accelerated by the thoughtful use of food aid.

Thus, with sensible policy at the national and international levels, we can obtain virtually complete food security over the next few decades. With judicious international policy, providing foreign assistance for both long-run development of the poor countries and short-run utilization of the surplus food of developed countries, we could achieve a close approximation of global food security within a decade. That is a grand prospect. In the course of only a few hundred years the whole world will have moved from a state of virtually universal food insecurity to a state of virtually universal food security.

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APPENDIX A
United States Colleges and Universities Offering Academic Programs in Agriculture

Alabama

Alabama Agricultural & Mechanical University
School of Agriculture and Home Economics
Normal, AL 25762
(205) 851-5783

Auburn University
College of Agriculture
Auburn, AL 36849-5401
(205) 844-2345

Tuskegee University
School of Agriculture and Home Economics
Tuskegee, AL 36088
(205) 727-8327 or 727-8157

Alaska

University of Alaska, Fairbanks
School of Agriculture and Land Resources Management
172 AHRB
Fairbanks, AK 99775-0100
(907) 474-7083

Arizona

Arizona State University
School of Agribusiness and Environmental Resources
Tempe, AZ 85287-3306
(602) 965-3585

Northern Arizona University
School of Forestry
P. O. Box 15018
Flagstaff, AZ 86011
(602) 523-6638

University of Arizona
College of Agriculture
Tuscon, AZ 85721
(602) 621-3613

Arkansas

Arkansas State University
College of Agriculture
P. O. Box 1080
State University, AR 72467
(501) 972-2085

Arkansas Tech University
Department of Agriculture
Russellville, AR 72801
(501) 968-0625

Southern Arkansas University
Department of Agriculture
P. O. Box 1343 SAU
Magnolia, AR 71753
(501) 235-4341

University of Arkansas
College of Agriculture and Home Economics
Fayetteville, AR 72701
(501) 575-2252

University of Arkansas, Monticello
Agriculture
P. O. Box 3508
Monticello, AR 71656-3508
(501) 460-1033 or 543-8132

University of Arkansas, Pine Bluff
School of Agriculture and Home Economics
Pine Bluff, AR 71601
(501) 543-8131 or 543-8132

California

California State Polytechnic University
College of Agriculture
San Luis Obispo, CA 93407
(805) 756-2161

California State Polytechnic University
College of Agriculture
3801 W. Temple Avenue

Pomona, CA 91768
(909) 869-2204

California State University, Chico
School of Agriculture and Human Environmental Sciences
317 Plumas Hall
Chico, CA 95929-0440

California State University, Fresno
School of Agricultural Sciences and Technology
Fresno, CA 93740-0079
(209) 278-2061

University of California, Berkeley
College of Natural Resources
101 Giannini Hall
Berkeley, CA 94720
(415) 642-0542

University of California, Davis
College of Agricultural and Environmental Sciences
228 Mrak Hall
Davis, CA 95616-8571
(916) 752-6971

University of California, Riverside
College of Natural and Agricultural Sciences
Riverside, CA 92521
(909) 787-7289

Colorado

Colorado State University
College of Agricultural Sciences
Fort Collins, CO 80523
(303) 491-6274

Connecticut

University of Connecticut
College of Agriculture and Natural Resources
Storrs, CT 06269
(203) 486-2919 or 486-2920

Delaware

Delaware State College
Department of Agriculture and Natural Resources
Dover, DE 19901
(302) 739-4929

University of Delaware
College of Agricultural Sciences
Newark, DE 19717-1303
(302) 831-2508

Florida

Florida A & M University
College of Engineering Sciences, Technology, and Agriculture
Tallahassee, FL 32307
(904) 599-3383

University of Florida
College of Agriculture
Gainesville, FL 32611
(904) 392-1961

Georgia

The Fort Valley State College
School of Agriculture, Home Economics, and Allied Programs
Fort Valley, GA 31030
(912) 825-6344

University of Georgia
College of Agricultural and Environmental Sciences
Athens, GA 30602
(706) 542-1611

Guam

University of Guam
College of Agriculture and Life Sciences
UOG Station
Mangilao, Guam 96923
(671) 734-2506

Hawaii

University of Hawaii
College of Tropical and Human Resources
3050 Maile Way
Honolulu, HI 96822
(808) 956-6997

Idaho

University of Idaho
College of Agriculture
Iddings Agricultural Sciences Building
Moscow, ID 83843
(208) 885-6446

Illinois

Illinois State University
Department of Agriculture

Normal, IL 61761
(309) 438-5654

SOUTHERN ILLINOIS UNIVERSITY
College of Agriculture
Carbondale, IL 62901
(618) 453-2469

WESTERN ILLINOIS UNIVERSITY
Applied Sciences/ Agriculture Department
503 Currens Hall
Macomb, IL 61455
(309) 298-1080

UNIVERSITY OF ILLINOIS
College of Agriculture
1301 West Gregory Drive
Urbana, IL 61801
(217) 333-3380

Indiana

PURDUE UNIVERSITY
School of Agriculture
1140 Agricultural Administration Building
West Lafayette, IN 47907-1140
(317) 494-8472

Iowa

IOWA STATE UNIVERSITY
College of Agriculture
Ames, IA 50011
(515) 294-6614

Kansas

FORT HAYS STATE UNIVERSITY
College of Agriculture
600 Park Street
Hays, KS 67601
(913) 628-4364

KANSAS STATE UNIVERSITY
College of Agriculture
Manhattan, KS 66506-4015
(913) 532-6151

Kentucky

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Center for International Forestry Research
(CIFOR)
Jalan Gunung Batu 5
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P. O. Box 6596
JKPWB Jakarta 10065
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62 (251) 31-9423, 32-4032, 31-4581, or 32-6458

Centro Internacional de Mejoramiento de Maiz y
Trigo (CIMMYT)
Lisboa 27
P. O. Box 6-641
06600 Mexico, D. F. Mexico
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Centro Internacional de la Papa (CIP)
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Consultative Group on International Agricultural
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The World Bank
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Food and Agricultural Organization of the United
Nations (FAO)
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International Atomic Energy Agency (IAEA)
Wagramerstrasse 5
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(43-1) 23600

International Center for Agricultural Research in
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(963-21) 225012, 225112, or 234890

International Center for Living Aquatic Resources
Management (ICLARM)
MC P. O. Box 2631, Makati Central Post Office
0718 Makati
Metro Manila
Philippines
(63-2) 817-5255 or 817-5163

International Centre for Research in Agroforestry
(ICRAF)
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(254-2) 521450

International Crops Research Institute for the Semi-
Arid Tropics (ICRISAT)
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International Food Policy Research Institute
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International Fund for Agricultural Development
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Dryland Farming
Desertification of Drylands; Fertilizer Management and Technology; Irrigation Engineering, Evapotranspiration; Irrigation Engineering: Farm Practices, Methods, and Systems; Meteorology; Nitrogen Cycling; Soil and Water Management and Conservation; Soil, Chemicals: Movement and Retention; Soil Fertility; Soil Genesis, Morphology, and Classification; Soil Management; Soil–Water Relationships; Tillage Systems; Water: Control and Use

E

Edible Tree Nuts: Pecan and Other Hickories
Entomology, Horticultural; Fungicides; Irrigation Engineering: Farm Practices, Methods, and Systems; Orchard Management: Soil Environment and Resources; Orchard Management Systems; Pest Management, Biological Control; Pest Management, Chemical Control; Pest Management, Cultural Control; Plant Pathology

Edible Tree Nuts, Walnuts
Edible Tree Nuts: Pecan and Other Hickories

Education: Children and Youth
Cooperative Extension Service; Education: Undergraduate and Graduate University; Women in Agriculture

Education: Undergraduate and Graduate University
Agricultural Experiment Stations; Cooperative Extension Service; Education: Children and Youth; Ethics; Rural Sociology; Women in Agriculture

Egg Production, Processing, and Products
Animal Nutrition, Nonruminant; Feeds and Feeding; Poultry Processing and Products; Poultry Production

Embryo Transfer in Domestic Animals
Animal Reproduction, Nonpregnant Female; Animal Reproduction, Pregnancy; Ethics; Transgenic Animals

Energy Utilization
Biomass; Corn Production; Fertilizer Management and Technology; Herbicides and Herbicide Resistance; Irrigation Engineering: Farm Practices, Methods, and Systems; Labor; Pest Management, Chemical Control; Production Economics; Quantitative Methods in Agricultural Economics; World Hunger and Food Security

Entomology, Horticultural
Integrated Pest Management; Plant Biotechnology: Food Safety and Environmental Issues; Plant Pathology; Plant Virology; Sustainable Agriculture

Entomology, Veterinary
Animal Diseases; Insect Physiology; Integrated Pest Management; Pest Management, Biological Control; Pest Management, Chemical Control; Pest Management, Cultural Control; Sustainable Agriculture

Environmental Horticulture
Floriculture; Horticultural Greenhouse Engineering; Integrated Pest Management; Pest Management, Biological Control; Plant Propagation; Plant Tissue Culture; Turfgrasses

Ethics
Dairy Cattle Production; Plant Biotechnology: Food Safety and Environmental Issues; Transgenic Animals

Evolution of Domesticated Plants
Cultivar Development; Dormancy; International Agricultural Research; Photosynthesis; Plant Genetic Enhancement; Plant Genetic Resource Conservation and Utilization; Plant Genetic Resources; Plant Physiology; Weed Science

F

Farming Systems
Cooperative Extension System; International Agricultural Research; Rural Sociology; Women in Agriculture

ISBN 0-12-226674-9
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