Growth and Mineral Nutrition of Field Crops

Third Edition

Nand Kumar Fageria
Virupax C. Baligar
Charles Allan Jones

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Preface

Many of mankind's successes during the second half of the twentieth century were dependent on the production of food outstripping population growth and our demand for food. During this period, green revolution technology helped increase the yields of important food crops like wheat, rice, corn, and soybeans at unprecedented rates. The main features of green revolution technology were semi-dwarf plant stature, disease and insect resistance, adequate plant nutrition, and the moisture required for higher productivity. Semi-dwarf cultivars with increased pest resistance produced greater grain yields per unit biomass, also known as harvest index. These new cultivars were very responsive to applied fertilizers (especially to nitrogen), were resistant to lodging, and their yield potentials were two to three times higher than cultivars available prior to the green revolution. In addition, these cultivars were resistant to multiple diseases and insects, which improved their yield stability. Green revolution technology led to increased production through higher productivity, thereby conserving arable land and forests. It has helped many developing countries, such as China, India, and Pakistan, achieve a balance between population growth and food production. The green revolution, however, did not link farming system sustainability to food system sustainability as a whole. In recent years, the rate of food-grain production has been lower than the rate of population growth. Furthermore, in recent decades, population growth has steadily reduced available agricultural land per capita from about 0.5 ha to half that figure, and in the next 20 years, it is projected to decline to about 0.15 ha. World population continues to increase by about 80 million people a year, an annual growth rate of 1.4%, with 90% of this increase occurring in the developing countries of Asia, Africa, and Latin America. By the middle of the twenty-first century, the world population is projected to be about 9 billion. As a result, world food production must increase by 50% on much the same land area as we farm today. To meet this challenge, we must develop the technology required by an "evergreen" revolution, one that increases crop productivity without degrading natural resources like land, water, and air. The aim of this new thrust is to increase food production well above the level obtained by the green revolution of the 1960s. This will require adapting technologies and policies that are both more productive and have less environmental impact than those now in use. These new technologies must be not only economically viable, but also environmentally sustainable and socially acceptable. Knowledge of crop growth, development, and nutritional requirements, and the judicious use of agricultural inputs, including chemical fertilizers and water, will be very important. This book covers all aspects of crop growth and mineral nutrition that contribute to sustainable, high-yield agriculture. The 19 chapters bring together international scientific knowledge of crop production as well as the impacts of agriculture on the environment, with an emphasis on the soil's ability to sustain high crop yields and healthy human populations.

The third edition of this book is meant to fill the same need that prompted writing the first and second editions. In writing this book, we have kept in mind several readers, including undergraduate and graduate students, professors, research scientists, extension workers, private company personnel, government administrators, and individuals developing public policy for research programs to improve crop production throughout the world. In addition, this book can be used by different disciplines of agricultural and environmental sciences, such as plant nutrition, plant physiology, plant biochemistry, plant ecology, soil science, agronomy, horticulture, range management, and environmental sciences.

We could not have written such a comprehensive book without the help of many people. We sincerely thank all of them. Dr. N. K. Fageria thanks the National Rice and Bean Research Center, Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA), Santo Antônio de Goiás, Brazil, for providing the facilities necessary to write this book. We would like to thank the staff at

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N. K. Fageria
National Rice and Bean Research Center
Empresa Brasileira de Pesquisa Agropecuária
Santo Antônio de Goiás, Brazil

V. C. Baligar
Beltsville Agriculture Research Center
Agriculture Research Service
United States Department of Agriculture
Beltsville, Maryland

Charles Allan Jones
Texas AgriLife Research and Extension Service
Urban Solutions Center
Dallas, Texas

Authors

N. K. Fageria, PhD in agronomy, is a senior research soil scientist at the National Rice and Bean Research Center, Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA), Santo Antônio de Goiás, Brazil, since 1975. He is a nationally and internationally recognized expert in the area of mineral nutrition of crop plants, is a research fellow, and has been an ad hoc consultant of the Brazilian Scientific and Technological Research Council (CNPq) since 1989. He is the author or coauthor of 9 books and more than 280 scientific journal articles, book chapters, review articles, and technical bulletins. Dr. Fageria has been invited several times by the editor of *Advances in Agronomy*, which is a well-established and highly regarded serial publication, to write review articles on nutrient management, enhancing nutrient use efficiency in crop plants, and ameliorating soil acidity by liming on tropical acid soils for sustainable crop production. He has been an invited speaker to several national and international congresses, symposia, and workshops. He is a member of the editorial board of the *Journal of Plant Nutrition* and the *Brazilian Journal of Plant Physiology*. He is also a member of the International Steering Committee of Symposium on Plant–Soil Interactions at Low pH since 1990.

V. C. Baligar, PhD, is a senior research scientist with United States Department of Agriculture-Agricultural Research Service (USDA-ARS) at Beltsville Agricultural Research Center, Beltsville, Maryland. He is the coauthor and coeditor of several books and over 250 scientific journal articles, book chapters, and review papers, and has been elected a fellow of the American Society of Agronomy and Soil Science Society of America. Dr. Baligar has served as advisor, consultant, and collaborator on international research programs in many countries in Europe, Asia, and South America.

Charles Allan Jones, PhD, is a professor at Texas AgriLife Research and Extension Service, Dallas, Texas. He is the author or coauthor of several books and over 90 publications, and has served as director of the Texas Water Resources Institute and as associate director of Texas AgriLife Research. Dr. Jones has worked as a crop physiologist in Texas, Hawaii, Australia, France, Colombia, and Brazil.

1 Field Crops and Mineral Nutrition

1.1 INTRODUCTION

In the agricultural sciences, soil fertility and plant nutrition played an important role during the twentieth century in increasing crop yields. In the twenty-first century, the importance of this field is expected to increase due to limited natural resources (land and water), the need for more sustainable agricultural systems, and concern about environmental pollution. In this context, increasing crop yields will be a major challenge to agricultural scientists, in general, and soil scientists, in particular. Increasing crop yields under these constraints will require a rational use of chemical fertilizers, an increasing use of organic sources of nutrients, a recycling of plant available nutrients, and an exploitation of the genetic potential of crop species and cultivars to make efficient use of nutrients.

The economic development of modern society depends on field crops for human consumption, animal feed, and as industrial raw materials for the production of clothing, plastics, energy, and other products. It is projected that the global population will exceed 7 billion by 2025. Arable land will decrease and biotic and abiotic stresses will expand. Food security, best defined as the economic, physical, and social access to a balanced diet and safe drinking water will be threatened, with a holistic approach to nutrition and nonnutrition factors needed to achieve success in the eradication of hunger (Swaminathan, 2007). Science and technology can play a very important role in stimulating and sustaining an **evergreen revolution** leading to long-term increases in productivity without degrading the environment (Swaminathan, 2007). Evergreen revolution technologies are based on a farming systems approach and will also involve farmer participatory breeding and knowledge management. An evergreen revolution needs the integration of frontier technologies like biotechnology and information communication technology with traditional ecological prudence (Swaminathan, 2006). Similarly, Wilson (2002) reported that the aim of an evergreen revolution is to lift food production well above the level obtained by the green revolution of the 1960s, using more advanced and much safer technology and regulatory policies than those now in existence. It is now widely agreed that new technologies must be not only economically viable, but also environmentally and socially sustainable. The term "ecotechnology" is used in the case of technologies that are rooted in the principles of ecology, economics, gender and social equity, employment generation, and energy conservation (Swaminathan, 2006). In this context, supplying adequate amounts of mineral nutrients to crops is one of the most important factors in achieving higher productivity. This book is a broad treatise on the mineral nutrition of field crops and provides an introduction to the management of the mineral nutrition of field crops. A brief account of these topics is given in this chapter.

1.2 FIELD CROPS

Field crops, often referred to as agronomic crops, are crops grown on a large scale for human consumption, livestock feed, and as raw materials for industrial products. Crops are grouped or classified on the basis of their botanical characteristics or of their utility, or both. It is by these criteria that the world's field crops are commonly grouped into cereals, pulses or grain legumes, fiber crops, oil crops, root crops, and rubber crops (Donald and Hamblin, 1983). The most important food crops are cereals and feed grains, such as wheat, rice, corn, barley, oats, and rye, and an assortment of

legumes. Feed crops include several of the same species of plants used for food, as well as forage and pasture crops, and in many instances food and fiber crop residues from some type of processing. Forages, when preserved by anaerobic fermentation, are termed silage crops, and when dried, are called hay crops.

Cereals such as wheat, rice, and corn are the world's dominant food crops. Their total global production is much higher than that of other food crops. These crops are dominant primarily because more breeding work has been done for them and secondarily, because they are grown mostly on better, often irrigated soils. Also, these crops occupy large areas in many parts of the world. The dominance of cereals is increasing because they tend to replace lower-yielding and less management-responsive crops. Nevertheless, excessive displacement of pulses by cereals can be undesirable, not only in terms of imbalance in human diets but also in terms of the maintenance of soil fertility, the incidence of pests and diseases, and the stability of farming systems.

The world average yields for all pulse crops are only about half of those for cereals and have shown a slower rate of increase in recent years. Record yields are also much lower. However, the lower biomass yields of pulses are offset in part by the higher calorie contents of proteins and lipids in the oilseed crops, such as soybean, rape, and sunflower. From comparisons of the known energy requirements of the various metabolic pathways, nutritionally equivalent seed yields are 60 for rape seed, 70 for soybean, 90 for peas, and 100 for wheat and corn (Evans, 1980).

The higher protein and lipid contents of pulse seeds appears to be related to the early mobilization of protein out of leaves, leading to a decline in their capacity for further photosynthesis and low biomass yield. The data in Table 1.1 show that the protein and lipid contents of legumes are much higher than those of cereals. The growth habit of legumes, particularly their progressive flowering and seed setting compared with the synchronous flowering of cereal crops, may also reduce their yield potential (Evans, 1980). In addition, legumes have higher photorespiration rates than warm-season cereals like corn and sorghum, which leads to lower yields of legumes (Fageria et al., 2006; Fageria, 2009).

TABLE 1.1
Protein and Lipid Contents in the Seed of Principal Cereal and Legume Species

Crop Species	Protein (g kg^{-1})	Lipid (g kg^{-1})
Rice	105	22
Wheat	113	17
Barley	132	35
Corn	102	41
Sorghum	88	35
Oat	125	47
Average of cereals	111	33
Soybean	314	201
Dry bean	192	24
Lupin	251	41
Adzuki bean	216	13
Peanut	193	304
Pea	233	15
Chickpea	173	51
Average of legumes	225	93

Sources: Adapted from Shinano, T. et al., *Soil Sci. Plant Nutr*., 39, 269, 1993; Fageria, N.K., *The Use of Nutrients in Crop Plants*, CRC Press, New York, 2009.

Finally, the growth cycle of legumes is generally shorter than that of cereals. This shorter vegetative growth period allows less time for nutrient uptake, which is why pulses typically require more fertile soils for high production than do cereals.

Among food crops, root crops such as potato, sweet potato, and cassava play an important role in supplying calories for the world population. It is generally thought that food produced by root crops is of inferior quality. Root crops are especially thought to contain less protein than grain crops. It is true that cereal grains generally contain 7%–11% protein, whereas root crops contain only 0.4%–2.8% (Vries et al., 1967). But for the determination of food quality, parameters other than protein must also be measured (Table 1.2). Rice, the most heavily consumed food crop in the world, does not compare favorably with root crops from a broad nutritional perspective (Table 1.2). It actually contains a little more protein than most root crops, but in other parameters of food quality the root crops are superior to rice. This is also true for the other grain crops. It may, therefore, be concluded that the grain crops are not superior to root crops in terms of food quality. Root crops deserve more attention in breeding and selection programs insofar as they have a far higher production of edible calories per day of vegetative growth than do cereals.

Higher yield played a major role in the increase in the total production of most agronomic crops in the last half century (Evans, 1998; Cassman, 1999; Egli, 2008). During the twentieth century (1950–1990), grain yields of cereals (wheat, corn, and rice) tripled worldwide. Wheat yields in India, for example, increased by nearly 400% from 1960 to 1985, and yields of rice in Indonesia and China more than doubled. The vastly increased production resulted from high-yielding varieties, improved irrigation facilities, and the use of chemical fertilizers, especially nitrogen. The results were very significant in Asia and Latin America, where the term **green revolution** was used to describe the process (Brady and Weil, 2002). Green revolution, defined as a commodity-centered increase in productivity, achieved by changes in plant architecture, improved grain harvest index and photoperiod insensitivity, resulted in the growth rate in food production exceeding the growth rate in population (Swaminathan, 2007). The green revolution was the product of alteration in plant architecture and physiological properties through breeding in wheat, rice, corn, sorghum, and other crops (Swaminathan, 2006). The semidwarf plant stature contributed to providing adequate nutrition to the plant for high productivity, without inducing lodging. It also increased the grain harvest index. Similarly, photoinsensitivity helped to match the crop cultivar to seasons with appropriate moisture availability. The green revolution led to increased production through higher productivity and thereby, conserved arable land and forests (Swaminathan, 2006).

The term "green revolution" was coined by Dr. William Gaud of the U.S. Department of Agriculture in 1968 to describe the revolutionary progress taking place in the wheat and rice

TABLE 1.2
Composition per 100 Calories Edible Portion of Some Important Grain and Root Crops

Crop	Protein (g)	Ca (mg)	Fe (mg)	Vitamin A (IU)	Thiamine (mg)	Riboflavin (mg)	Nicotinamide (mg)	Ascorbic Acid (mg)
Rice	2.0	1.4	0.28	±0	0.02	0.01	0.28	0
Wheat	3.2	5.8	0.73	±0	0.09	0.02	0.58	0
Corn	2.8	3.3	0.69	30–170	0.09	0.04	0.55	0
Sorghum	2.9	9.0	1.26	±0	0.12	0.03	0.98	0
Sweet potato	0.35–2.5	21.9	0.90	0–3500	0.09	0.04	0.61	26
Cassava	0.46	16.3	0.65	±0	0.46	0.02	0.46	20
Yam	1.9	9.6	1.1	0–190	0.09	0.03	0.38	9

Source: Compiled from Platt, B.S., Tables of representative values of foods commonly used in tropical countries, in *Medical Research Council Special Report Series* 302, HMSO, London, U.K., 46 pp, 1965.

fields of South Asia, in terms of yield per hectare. The initial genetic material for the new plant architecture and physiological rhythm came from the International Maize and Wheat Improvement Center (CIMMYT) in Mexico in the case of wheat, and the International Rice Research Institute (IRRI) in the Philippines for rice. The original genes for the semidwarf trait were derived from the "Norin 10" wheat from Japan and the "Dee-gee-woo-gen" dwarf rice of China. Increased yield came from the interaction of the genotype and the high-yielding environment, which was created by the application of inorganic fertilizers, especially nitrogen and irrigation water (Swaminathan, 2006). The increase in productivity of annual crops with the application of fertilizers and lime in the Brazilian Cerrado or Savanna region during the 1970s and 1980s is another example of the twentieth century expansion of the agricultural frontier in acid soils (Borlaug and Dowswell, 1997; Fageria, 2009).

1.3 MINERAL NUTRITION

Mineral nutrition includes the supply, absorption, and utilization of essential nutrients for the growth and the yield of crop plants. No one knows with certainty when humans first incorporated organic substances, manures, or wood ashes as fertilizer into the soil to stimulate plant growth. However, it is documented in writings as early as 2500 BC that humans recognized the richness and fertility of alluvial soils in valleys of the Tigris and the Euphrates rivers (Tisdale et al., 1985). Forty-two centuries later, scientists were still trying to determine whether plant nutrients ingested by plant roots were derived from water, air, or soil. Early progress in the development of the understanding of soil fertility and plant nutrition concepts was slow, although the Greeks and Romans made significant contributions in the years 800–200 BC (Westerman and Tucker, 1987). It was mainly to the credit of Justus von Liebig (1803–1873) that the scattered information concerning the importance of mineral elements for plant growth was collected and summarized, and that mineral nutrition of plants was established as a scientific discipline (Marschner, 1983).

In 1840, Liebig published results from his studies on the chemical analysis of plants and the mineral contribution of soils. These studies initiated modern research on plant nutrition and highlighted the importance of individual minerals in stimulating plant growth. From these studies evolved the concept that individual minerals were limiting factors for the growth potential of plants (Sinclair and Park, 1993). These findings led to a rapid increase in the use of chemical fertilizers. By the end of the nineteenth century, large amounts of potash, superphosphate, and, later, inorganic nitrogen were used in agriculture and horticulture to improve plant growth, especially in Europe (Marschner, 1995). Notwithstanding these, it was not until the twentieth century that the list of 17 essential elements was completed and the fundamental concepts of plant nutrition were developed. The quest for an understanding of plant nutrition is not yet complete (Glass, 1989).

Plants contain small amounts of 90 or more elements, but only 17 elements are known to be essential for plant growth (Fageria, 1984, 2009; Epstein and Bloom, 2004). Essential nutrients are divided into two groups on the basis of the quantity required by plants. Those required in large quantities are classified as macronutrients and those required in small amounts as micronutrients. Carbon, hydrogen, oxygen, nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur are known as macronutrients. In the group of micronutrients are iron, manganese, boron, zinc, copper, molybdenum, chlorine, and nickel. Micronutrients have also been called minor or trace elements, indicating that their concentrations in plant tissues are minor or in trace amounts relative to the macronutrients (Mortvedt, 2000). Chlorine has often been referred to as a micronutrient even though its concentrations in plant tissues is often equivalent to that of macronutrients (Fageria et al., 2002). Sodium, silicon, selenium, vanadium, and cobalt are beneficial for some plants but have not been established as essential elements for all higher plants (Mengel et al., 2001; Fageria et al., 2002; Daroub and Snyder, 2007). Possibly, other essential micronutrients will be discovered in the future because of the recent advances in solution-culture techniques and the availability of highly sensitive analytical instruments.

Micronutrients are normally constituents of prosthetic groups that catalyze redox processes by electron transfer, such as with the transition elements Cu, Fe, Mn, and Mo, and form enzyme–substrate complexes by coupling an enzyme with a substrate (Fe and Zn) or enhance enzyme reactions by influencing molecular configurations between an enzyme and a substrate (Zn) (Römheld and Marschner, 1991). Except for B and Cl, the essential micronutrients are metals (Fageria et al., 2002). Even though micronutrients are required in small quantities by field crops, their influence is as large as that of macronutrients in crop production. Micronutrient deficiencies in crop plants are widespread because of (1) increased micronutrient demands from intensive cropping practices and adoption of high-yielding cultivars that may have a higher micronutrient demand, (2) an enhanced production of crops on marginal soils that contain low levels of essential nutrients, (3) an increased use of high analysis fertilizers with low amounts of micronutrients, (4) a decreased use of animal manures, composts, and crop residues, (5) the use of many soils that are inherently low in micronutrient reserves, and (6) the involvement of natural and anthropogenic factors that limit adequate supplies and create element imbalances (Fageria et al., 2002).

Numerous soil, plant, microbial, and environmental factors affect plant acquisition of micronutrients. Soil pH, redox potential, and organic matter (OM) have profound effects on the bioavailability of micronutrients (Fageria et al., 2002). Soil OM unquestionably contains the largest pool of micronutrients in soil, and influences micronutrient cycling, the distribution of naturally occurring organic ligands, the speciation and the form (organic or inorganic) of elements in soil solution, and the nature and the stability of micronutrient complexes with humic and fulvic acids (Stevenson, 1991). Organic substances like humic and fulvic acids formed during soil OM degradation and transformation are important in micronutrient cycling (Stevenson, 1986; Fageria et al., 2002).

Macro- and micronutrient classification is simply based on the amount required. All nutrients are equally important for plant growth. If deficiency of any nutrient occurs in the growth medium, plant growth is adversely affected. Soil and plant analyses are commonly used to identify nutritional deficiencies in crop production. The best criterion, however, for diagnosing nutritional deficiencies in annual crops is through the evaluation of crop responses to applied nutrients. If a given crop responds to an applied nutrient in a given soil, this means that the nutrient is deficient for that crop. The relative decrease in yield in the absence of a nutrient as compared to an adequate soil fertility level can give an idea of the magnitude of nutrient deficiency. A study was conducted at the National Rice and Bean Research Center of EMBRAPA, Santo Antônio de Goiás, Brazil, to provide evidence of which nutrients were most yield-limiting for the production of several annual crops on an Oxisol (Figure 1.1).

The magnitude of yield reduction of five annual crops without the application of 12 essential plant nutrients in an Oxisol varied from crop to crop and from nutrient to nutrient. Phosphorus and calcium were the most yield-limiting nutrients among the five crops tested, except upland rice, which was not sensitive to Ca deficiency. Among micronutrients, B followed by Zn were the most yield-limiting nutrients for common bean. Molybdenum and zinc were the most yield-limiting for upland rice, Zn, Cu, and Mn for soybean, Zn, B, and Mo for corn, and Mn was the most yield-limiting for the wheat crop. Among the five crops tested, the susceptibility to P deficiency based on top dry matter yield was in the order of upland rice > common bean > soybean > corn > wheat. The order of susceptibility for Ca deficiency was common bean > wheat > corn > soybean > upland rice. This means, upland rice was most tolerant to soil acidity, and common bean had the least tolerance among the crops tested. Similarly, the importance of N, P, and K fertilization on the growth of upland rice in Brazilian Oxisol is shown in Figure 1.2. For the growth of the tops of upland rice, P was the most yield-limiting nutrient followed by N and K.

Macronutrients are needed in concentrations of 1000 μg g^{-1} of dry matter or more, whereas micronutrients are needed in tissue concentrations equal to or less than 100 μg g^{-1} of dry matter (Oertli, 1979). Similarly, data in Figure 1.3 showed that the accumulation of macronutrients such as N, P, K, Ca, and Mg in the dry bean tops are much higher compared to micronutrients such as Fe, Mn, Zn, and Cu. The low requirement of plants for trace or micronutrients can be accounted for by the participation of these elements in enzymatic reactions and as constituents of growth

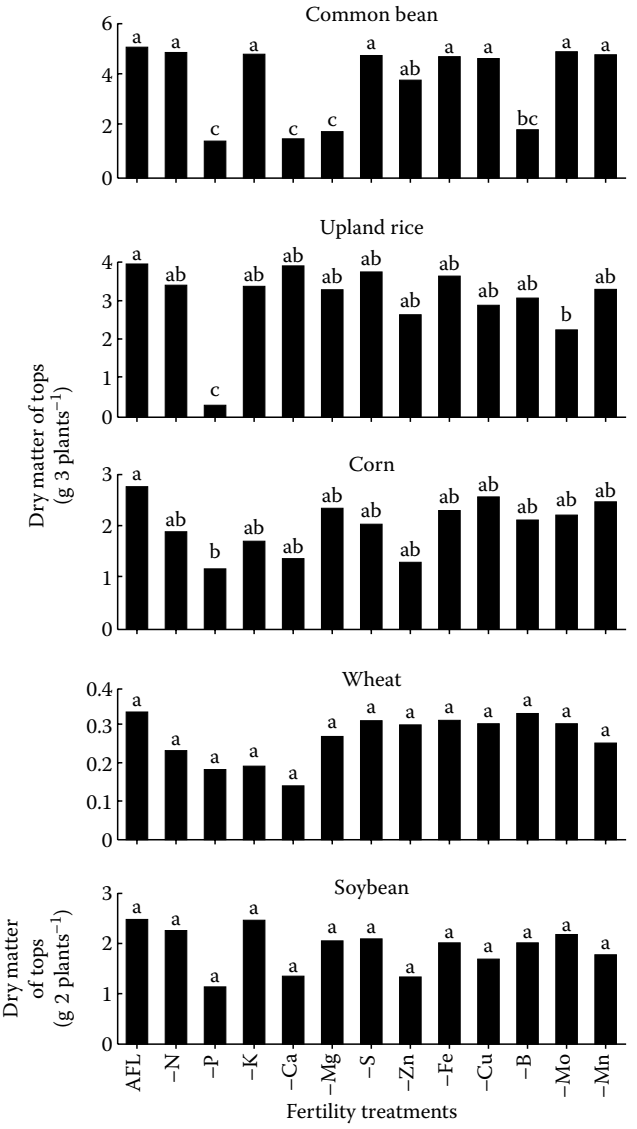

FIGURE 1.1 Response of five annual crop species to different fertility levels on an Oxisol. AFL = adequate fertility level, and minus (–) sign against each nutrient means without application of the nutrient. Different letters above each bar indicate significant differences between treatments by Tukey's test at a 5% probability level.

hormones rather than as components of major plant products, such as structural and protoplasmic tissue (Stevenson, 1986). As can be seen from Table 1.3, macronutrients play a major role in plant structure, whereas micronutrients are principally involved in enzymatic processes.

In the literature, the term "mineral nutrition" is very common and is often used to refer to essential plant nutrients. This is a slight misnomer, in that plant nutrients are not minerals. The term comes from the fact that most essential elements combine with other elements to form minerals, which eventually break down into their component parts. Mineral nutrients include all essential plant nutrients other than carbon, hydrogen, and oxygen, which are derived from CO_2 and H_2O, and nitrogen that originally came from atmospheric N_2 (Bennett, 1993).

Essential plant nutrients can also be classified as metals or nonmetals. The metals include K, Ca, Mg, Fe, Zn, Mn, Cu, and Mo. The nonmetals include N, P, S, B, and Cl (Bennett, 1993). According

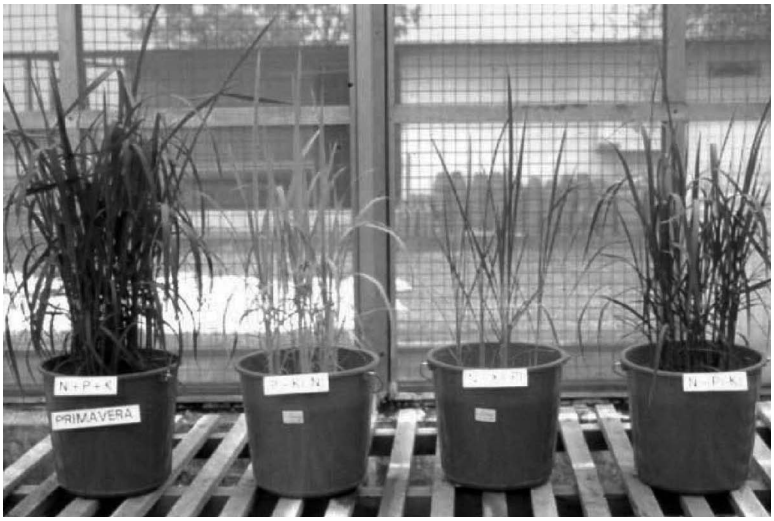

FIGURE 1.2 Growth of upland rice with the fertilization of N+ P+ K and the omission of N, P, and –K in Brazilian Oxisol. Pots from left to right, N+ P+ K, without N, without P, and without K fertilization. (From Fageria, N.K., *The Use of Nutrients in Crop Plants*, CRC Press, New York, 2009.)

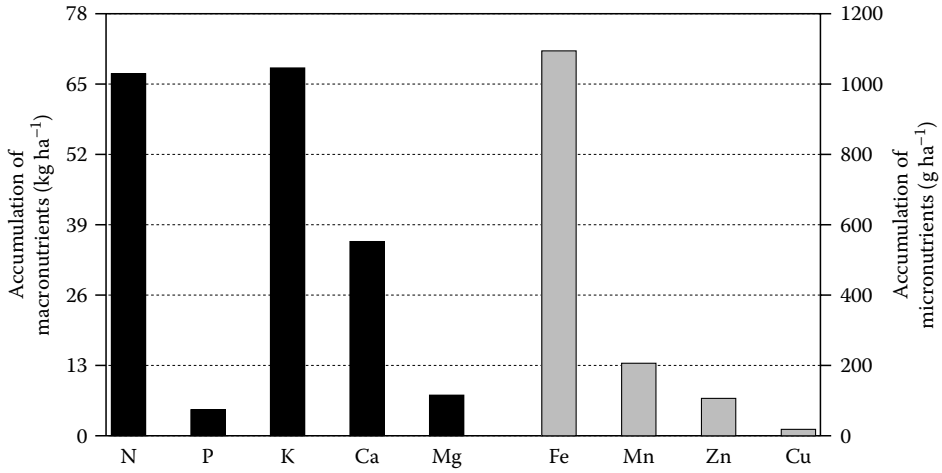

FIGURE 1.3 Accumulation of macro- and micronutrients in dry bean plant tops at flowering.

to Mengel et al. (2001), the classification of plant nutrients based on their biochemical behavior and their physiological functions seems more appropriate. Based on such a physiological approach, plant nutrients may be divided into the following four groups:

Group 1: C, H, O, N, and S. These nutrients are major constituents of organic material, involved in enzymic processes and oxidation–reduction reactions.

Group 2: P and B. These elements are involved in energy-transfer reactions and esterification with native alcohol groups in plants.

Group 3: K, Ca, Mg, Mn, and Cl. This group plays osmotic and ion balance roles, plus more specific functions in enzyme conformation and catalysis.

Group 4: Fe, Cu, Zn, and Mo. Present as structural chelates or metallo-proteins, these elements enable electron transport by valence change.

TABLE 1.3
Functions of Essential Nutrients in Plants

Nutrient	Function
Carbon	Basic molecular component of carbohydrates, proteins, lipids, and nucleic acids.
Oxygen	Oxygen is somewhat like carbon in that it occurs in virtually all organic compounds of living organisms.
Hydrogen	Hydrogen plays a central role in plant metabolism. Important in ionic balance and as the main reducing agent and plays a key role in the energy relations of cells.
Nitrogen	Nitrogen is a component of many important organic compounds ranging from proteins to nucleic acids.
Phosphorus	Central role in plants is in energy transfer and protein metabolism.
Potassium	Helps in osmotic and ionic regulation. Potassium functions as a cofactor or activator for many enzymes of carbohydrate and protein metabolism.
Calcium	Calcium is involved in cell division and plays a major role in the maintenance of membrane integrity.
Magnesium	Component of chlorophyll and a cofactor for many enzymatic reactions.
Sulfur	Sulfur is somewhat like phosphorus in that it is involved in plant cell energetic processes.
Iron	An essential component of many heme and nonheme Fe enzymes and carriers, including the cytochromes (respiratory electron carriers) and the ferredoxins. The latter are involved in key metabolic functions such as N fixation, photosynthesis, and electron transfer.
Zinc	Essential component of several dehydrogenases, proteinases, and peptidases, including carbonic anhydrase, alcohol dehydrogenase, glutamic dehydrogenase, and malic dehydrogenase, among others.
Manganese	Involved in the O_2-evolving system of photosynthesis and is a component of the enzymes arginase and phosphotransferase.
Copper	Constituent of a number of important enzymes, including cytochrome oxidase, ascorbic acid oxidase, and laccase.
Boron	The specific biochemical function of B is unknown but it may be involved in carbohydrate metabolism and in the synthesis of cell wall components.
Molybdenum	Required for the normal assimilation of N in plants. An essential component of nitrate reductase as well as nitrogenase (N_2 fixation enzyme).
Chlorine	Essential for photosynthesis and as an activator of enzymes involved in splitting water. It also functions in osmoregulation of plants growing on saline soils.
Nickel	Nickel is essential for urease, hydrogenases, and methyl reductase and for urea and ureide metabolism, to avoid toxic levels of these nitrogen fixation products in legumes. Nickel is a constituent of plant enzyme urease, the enzyme that catalyzes the degradation of urea to carbon dioxide and ammonia. Nickel-deficient plants accumulate toxic levels of urea in leaf tips, because of reduced urease activity.

Sources: Compiled from Oertli, J.J., Plant nutrients, in *The Encyclopedia of Soil Science*, Part 1, Fairbridge, R.W. and Finkl, C.W., Jr. (eds), Dowden, Hutchinson & Ross, Stroudsburg, PA, 382–385, 1979; Ting, I.P., Plant mineral nutrition and ion uptake, *Plant Physiology*, Addison-Wesley, Reading, MA, 331–363, 1982; Stevenson, F.J. (ed.), The micronutrient cycle, *Cycles of Soil*, Wiley, New York, 321–367, 1986; Daroub, S. and Snyder, G.H., The chemistry of plant nutrients in soil, in *Mineral Nutrition and Plant Disease*, Datnoff, L.E. et al. (eds.), The American Phytopathological Society, St. Paul, MN, 1–7, 2007; Fageria, N.K. and Baligar, V.C., *Adv. Agron*., 88, 97, 2005a; Fageria, N.K. and Baligar, V.C., Nutrient availability, in *Encyclopedia of Soils in the Environment*, Hillel, D. (ed.), Elsevier, San Diego, CA, 63–72, 2005b; Fageria, N.K., *The Use of Nutrients in Crop Plants*, CRC Press, New York, 2009.

Even though some of these elements have been known since ancient times, their essentiality has been established only within the last century (Tamhane et al., 1966; Marschner, 1995; Rice, 2007). The discovery of essential nutrients, their chemical symbols, and their principal forms for uptake are presented in Table 1.4.

Now the question arises, "What are the criteria of essentiality of nutrients for plant growth?" Arnon and Stout (1939) and Arnon (1950) proposed certain criteria of essentiality of mineral

TABLE 1.4
Essential Nutrients for Plant Growth, Their Principal Forms for Uptake, and Discovery

Nutrient	Chemical Symbol	Principal Forms for Uptake	Year of Discovery	Discovered Essential to Plants By
Carbon	C	CO_2	1882	J. Sachs
Hydrogen	H	H_2O	1882	J. Sachs
Oxygen	O	H_2O, O_2	1804	T. De Saussure
Nitrogen	N	NH_4^+, NO_3^-	1872	G. K. Rutherford
Phosphorus	P	$H_2PO_4^-$, HPO_4^{2-}	1903	Posternak
Potassium	K	K^+	1890	A. F. Z. Schimper
Calcium	Ca	Ca^{2+}	1856	F. Salm-Horstmar
Magnesium	Mg	Mg^{2+}	1906	Willstatter
Sulfur	S	SO_4^{2-}, SO_2	1911	Peterson
Iron	Fe	Fe^{2+}, Fe^{3+}	1860	J. Sachs
Manganese	Mn	Mn^{2+}	1922	J. S. McHargue
Boron	B	H_3BO_3	1923	K. Warington
Zinc	Zn	Zn^{2+}	1926	A. L. Sommer and C. B. Lipman
Copper	Cu	Cu^{2+}	1931	C. B. Lipman and G. MacKinney
Molybdenum	Mo	MoO_4^{2-}	1938	D. I. Arnon and P. R. Stout
Chlorine	Cl	Cl^-	1954	T. C. Broyer et al.
Nickel	Ni	Ni^{2+}	1987	Welch and Eskew

Sources: Adapted from Fageria, N.K. and Baligar, V.C., Nutrient availability, in *Encyclopedia of Soils in the Environment*, Hillel, D. (ed.), Elsevier, San Diego, CA, 63–72, 2005b; Fageria, N.K., *The Use of Nutrients in Crop Plants*, CRC Press, New York, 2009.

nutrients long ago, and these criteria are still valid. According to these researchers, the essentiality of a nutrient is based on the following criteria:

1. Omission of the element in question results in abnormal growth, failure to complete the life cycle (i.e., from seed germination to the production of viable seeds), or premature death of the plant.
2. The element forms part of a molecule or a constituent of the plant that is itself essential in the plant. Examples are N in protein and Mg in chlorophyll.
3. The element exerts its effect directly on growth or metabolism and not by some indirect effect such as antagonism of another element present at a toxic level.

1.4 SUMMARY

Crops are plants grown on a large scale for human consumption, livestock feed, and raw materials for industrial products. On the basis of the area planted and world production, the important field crops are wheat, rice, corn, barley, sorghum, potato, soybeans, sugarcane, sweet potatoes, cassava, sugar beet, rye, groundnuts, and cotton. This does not mean that other crops are not important. Plant nutrition is the process of nutrient application to the soil, the movement of nutrients to plant roots, the absorption by roots, and the translocation and the utilization in plants. Numerous soil, plant, microbial, and environmental factors affect nutrient availability to crop plants. These factors vary from region to region and sometimes even from field to field in the same region. Research data are needed for each crop species, and often different crop cultivars, for different agroecological regions

and socioeconomic conditions of the growers. Experimental work needs to be done under field and controlled conditions to generate basic and applied information. Hence, research on the supply of essential nutrients to crop plants in adequate amounts and of proper balance related to soil fertility and plant nutrition is a very dynamic, complex, and challenging issue for agricultural scientists.

Seventeen nutrients are essential for plant growth. These are C, H, O, N, P, K, Ca, Mg, S, Zn, Cu, Fe, Mn, B, Mo, Cl, and Ni. The first three (C, H, O) make up about 95% of plant dry weight and are supplied to plants by air and water. Chlorine can also be supplied by air. Soils, often with the help of humans have to furnish the rest (13 nutrients) in adequate amounts to obtain good crop yields. Even though research information on the mineral nutrition of plants has advanced significantly in recent years, most of the advances have been associated with macronutrients. Information on micronutrients is still insufficient. Reasons for this may be that micronutrients are required in very small amounts and their deficiencies have not been systematically verified under field conditions.

Agricultural productivity gains since the 1950s have resulted from the development of farming systems that have relied heavily on the use of high quantities of inorganic fertilizers, particularly N (Fageria and Baligar, 2005a). The average percentage of yield attributable to fertilizer generally ranged from about 40% to 60% in the United States and the United Kingdom and tended to be much higher in the tropics (Stewart et al., 2005). Recently calculated budgets for N, P, and K indicate that commercial fertilizer makes up the majority of nutrient inputs necessary to sustain current crop yields in the United States. Stewart et al. (2005) concluded that the commonly cited generalization that at least 30%–50% of crop yield is attributable to commercial fertilizer nutrient inputs is a reasonable, if not conservative estimate. Presently, 50% of the human population relies

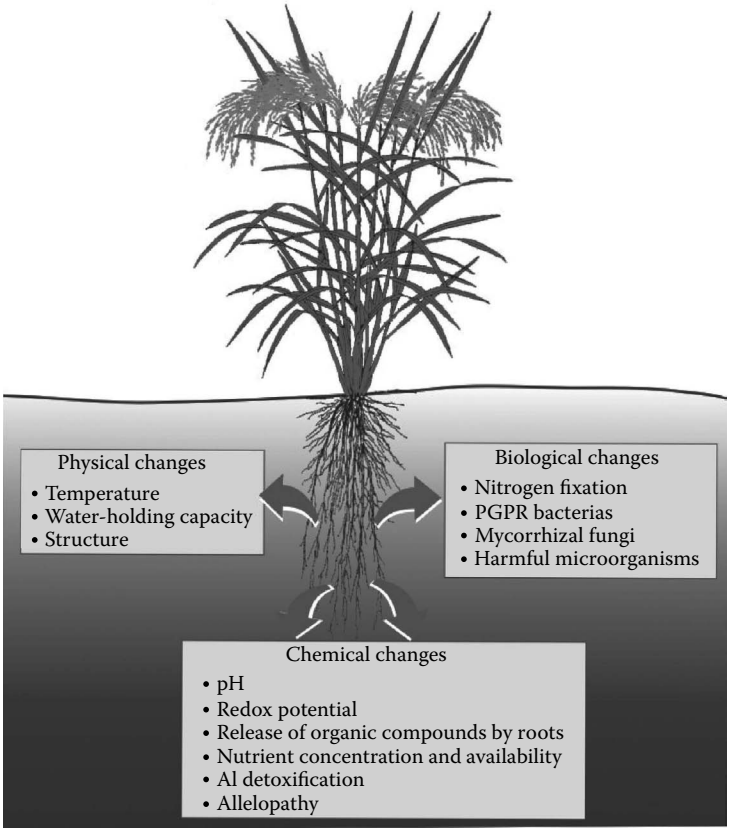

FIGURE 1.4 Physical, chemical, and biological changes in the rhizosphere. (From Fageria, N.K. and Stone, L.F., *J. Plant Nutr.*, 29, 1327, 2006.)

on nitrogen fertilizer for food production. About 60% of the global N fertilizer is used for producing the world's three major cereals—wheat, rice, and corn (Ladha et al., 2005). It is projected that 50%–60% more cereal grain will be required by 2025 to feed about 9.3 billion people (Ladha et al., 2005). Hence, a sustainable management of the agroecosystems in the twenty-first century faces unprecedented challenges. Under these situations, the use of N fertilizers will increase significantly if the efficiency with which N is used by the crop is not improved. The average N recovery efficiency by annual crops is about 40% (Fageria, 2009). This low N efficiency represents a significant cost to farmers and has important consequences for the ecosystem and human health as N moves beyond the farm in aqueous or gaseous forms (Galloway, 1998; Matson et al., 1998; Lobell, 2006). Raising crop yields to meet growing food demand while simultaneously reducing the environmental impacts of agriculture will require substantial improvements in nutrient use efficiency (Lobell, 2006).

Nutrient availability to plants is controlled by several processes in the soil–plant system before a nutrient is absorbed or utilized by the plant. Climatic, soil, and plant factors and their interactions affect all these processes. These factors vary from region to region and even within the same region. Some of the physical, chemical, and biological factors in the rhizosphere that significantly affect nutrient availability to field crops are given in Figure 1.4. The specific mineral nutrient requirements of important field crops are discussed in the chapters devoted to those crops.

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2 Factors Affecting Production of Field Crops

2.1 INTRODUCTION

Crop species, grown throughout the world, experience environmental stresses that limit their growth, development, and the full expression of their genetic potential for agronomic yield (Burker et al., 2004). A comparison of average crop yields with reported record yields has shown that the major crops grown in the United States exhibit annual average yields three- to sevenfold lower than record yields due to unfavorable environmental conditions (Boyer, 1982). An analysis of yields from corn (*Zea mays* L.), wheat (*Triticum aestivum* L.), soybean (*Glycine max* L. Merr.), sorghum (*Sorghum vulgare* L.), potato (*Solanum tuberosum* L.), sugarbeet (*Beta vulgaris* L.), oat (*Avena sativa* L.), and barley (*Hordeum vulgare* L.) revealed that the average yield represented only 22% of the mean record yield (Burke et al., 2004). Mineral nutrition is one of the most important single factors affecting the yield of annual crops (Fageria, 2009). In most agricultural situations, several factors interact with mineral nutrition over the course of the cropping cycle to limit the growth and the economic yield of crops (Fageria, 2009). Some factors, such as water, cultivar characteristics, nutrients, insects, and diseases, can be controlled to some degree by the farmers, and most crop management practices are directed at balancing the levels of control to obtain maximum economic returns. When such controls are successful, and these factors are not limiting to the growth of plants suitably adapted to the prevailing climate, maximum productivity depends principally on the rates of light interception and carbon dioxide assimilation by the crop surface (Loomis and Williams, 1963; Sinclair and Muchow, 1999; Fageria et al., 2006). This chapter is meant to serve as a brief review of the many factors that can limit the production of field crops. A subsequent chapter will deal in much greater detail with the limitations of mineral nutrition on the growth and economic yields of the world's major field crops.

Before discussing factors affecting the production of field crops, it is important to define the term crop productivity. Crop productivity or yield is the measurable production of a crop (Zadoks and Schein, 1979). According to Westlake (1963), the weight of new organic matter created by photosynthesis over a period, expressed as a rate, becomes crop productivity. Crop productivity or biomass yield is a function of environment, plant, management, and social–economic factors and their interaction. Mathematically, crop yield can be expressed by the following equation:

$$Y = f(E, P, M, S)$$

where
Y = yield
f = factors
E = environment
P = plant
M = management
S = social–economic

Figure 2.1 shows factors affecting crop yield. The maximum biomass yield of a crop in a given environment is possible only when all these factors are at optimum levels. If any one of these

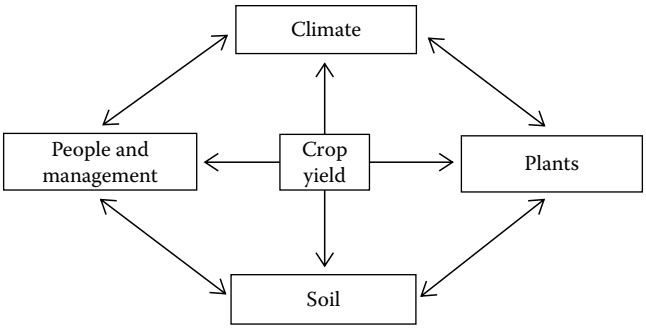

FIGURE 2.1 Factors affecting crop yield.

factors is limiting, the crop biomass yield will decrease. Similarly, economic yields (for example, seed yields) of crops are affected by the same environmental and cultural factors.

Clearly, crop productivity, whether expressed as biomass or economic yield, is a very complex phenomenon and it is not an easy task to improve and/or stabilize it. In the past decade, both the biomass and economic yields of important field crops have been improved through the use of improved cultivars, fertilizers, irrigation, fungicides, insecticides, and herbicides and improved cultural practices (Fageria et al., 2008; Fageria, 2009). All these can be classified as technological factors. How different factors affect crop production is discussed in this chapter.

2.2 ENVIRONMENTAL FACTORS

The environment of a plant may be defined as the sum of all external forces and substances affecting the growth, the structure, and the reproduction of that plant (Billings, 1952; Fageria, 1992). Crop environment is composed of climatic and soil factors that exert a great influence on plant growth and, consequently, yield. Climatic factors such as temperature, solar radiation, and moisture supply play an important role in crop production. Similarly, soil physical, chemical, and biological properties are directly related to crop productivity (Fageria, 2002; Fageria and Stone, 2006).

2.2.1 Climatic

Climate is one of the most important factors determining where crops can be grown, the composition of the nature of the natural vegetation, the characteristics of the soils, and the type of farming that can be practiced in a given agroecological region. From an agricultural point of view, there are two main types of climates: tropical and temperate. It is sometimes assumed that temperate climate means cold weather and tropical climate, hot weather. However, in temperate regions, temperatures are not always lower than in tropical regions. On the basis of mean annual temperatures, the boundaries between tropical and temperate climates, reported by various workers, varies from 18°C (64.4°F) to 23°C (73.4°F). Above this temperature range the climate may be considered tropical and below this range it may be considered temperate. However, a more appropriate indicator of tropical climates is their temperature stability during most parts of the year. In the tropics, the mean monthly temperature variation is typically 5°C (9°F) or less between the average temperatures of the three warmest and the average of the three coldest months (Sanchez, 1976). In fact, at high elevations in the tropics, temperatures can be too cool throughout the year to grow many crops produced in temperate regions. The important components of climate that affect crop growth are discussed below.

2.2.1.1 Temperature

Soil and air temperatures are important and often critical environmental factors for plant growth and productivity. In temperate regions, the temperatures often determine the length of the growing season, with cool temperatures in the spring and autumn limiting the growing season of warm-season crops

TABLE 2.1
Optimum Soil Temperature for Maximum Yield of Important Field Crops

Crop	Optimal Temperature (°C)	Reference
Barley (*Hordeum vulgare* L.)	18	Power et al. (1970)
Oats (*Avena sativa* L.)	15–20	Case et al. (1964)
Wheat (*Triticum aestivum* L.)	20	Whitfield and Smika (1971)
Corn (*Zea mays* L.)	25–30	Dormaar and Ketcheson (1960)
Cotton (*Gossypium hirsutum* L.)	28–30	Pearson et al. (1970)
Potato (*Solanum tuberosum* L.)	20–23	Epstein (1966)
Rice (*Oryza sativa* L.)	25–30	Owen (1971)
Bean (*Phaseolus vulgaris* L.)	28	Mack et al. (1964)
Soybean (*Glycine max* L. Merr.)	30	Voorhees et al. (1981)
Sugar beet (*Beta vulgaris* L.)	24	Radke and Bauer (1969)
Sugarcane (*Saccharum officinarum* L.)	25–30	Hartt (1965)
Alfalfa (*Medicago sativa* L.)	28	Heinrichs and Nielsen (1966)

and hot summer temperatures limiting the season for cool-season crops. In tropical regions, the mean temperatures are negatively correlated with the altitude, and crops with high optimum temperatures are grown at lower elevations than crops that grow better in cooler temperatures. Root temperature is influenced by the intensity, the quality, and the duration of solar radiation, air temperature, surface vegetation, and the color and thermal conductivity of the soil. In temperate climates, root temperatures often limit the planting dates of warm-season crops. Since soils warm more slowly in the Spring than does the air, soil temperatures are often the factor that farmers consider most important in determining the planting dates for summer crops (Nielsen, 1974). The optimum temperature for the maximum production of root material for several species ranges from 20°C to 30°C (Voorhees et al., 1981). The optimum soil temperature for the maximum yield of important field crops is presented in Table 2.1.

In general, the rates in plant processes are restricted when temperatures are too low, reach their maximum at somewhat higher temperatures, and decrease again when temperatures are too high. Figure 2.2 shows a strong negative relationship between rice grain yields at increasing canopy

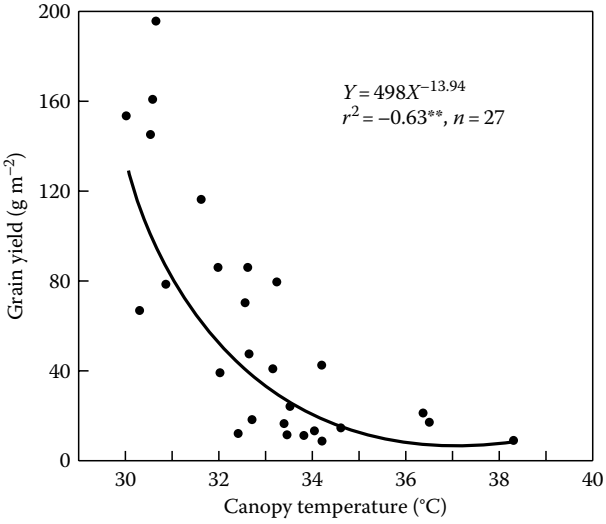

FIGURE 2.2 Relationship between rice grain yield and canopy temperature at 50% flowering. (From Garrity, D.P. and O'Toole, J.C., *Agron. J.*, 87, 773, 1995. With permission.)

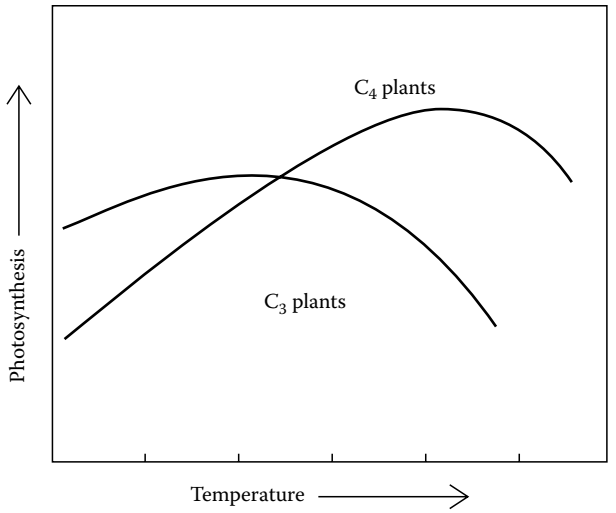

FIGURE 2.3 Relationship between temperature and photosynthesis in C_3 and C_4 plants. C_3 plants have an optimum temperature for photosynthesis at around 25°C and C_4 plants at around 35°C.

temperatures from 30°C to 38.5°C. Although there are exceptions, crops with C_4 photosynthetic metabolism are generally more tolerant of high temperatures and more sensitive to low temperatures than crops with C_3 photosynthesis (Edwards et al., 1983). For example, C_4 plants like sugarcane and corn, are able to grow better under high temperatures than are C_3 plants, such as wheat and barley. The tolerance of C_3 plants to low temperatures, and thus, their generally better photosynthetic performance under these conditions, compared to C_4 plants may be due in part to differences in the levels of certain photosynthetic enzymes, the cold lability of some key enzymes of the C_4 pathway, and the differences in the phase transition of lipids in membranes (Edwards et al., 1983). Figure 2.3 shows the relationship between temperature and photosynthesis in typical C_3 and C_4 plants.

2.2.1.2 Moisture Supply

Moisture availability is one of the most important factors determining crop production. The distribution of vegetation in an agroecological region is controlled more by the availability of water than by any other single factor. Water is required by plants for the translocation of mineral elements, for the manufacture of carbohydrates, and for the maintenance of the hydration of the protoplasm. Crop yield can be reduced at both very low and very high levels of moisture. Excess moisture reduces soil aeration and thus the supply of O_2 available to roots. With poor aeration, the activities of beneficial microorganisms and the water and the nutrient uptake by plants can be seriously inhibited though aquatic plants and rice are adapted to and function well even when soils are saturated. Soil moisture deficits can cause stomata in the leaf to close, reducing transpiration and helping maintain hydration of protoplasm, but also reducing photosynthesis. Moisture stress also causes reductions in both cell division and cell elongation, and hence, in growth. Figure 2.4 shows the relationship between the diameter of the head of a sunflower and water supply. The head size increased with the increase in irrigation water up to about 35 cm. It then leveled off as the amount of water applied increased up to 46 cm.

The supply of water (W), as expressed by the hydrological budget, is equal to precipitation (P) plus irrigation (I) and the change in storage (S), less runoff (R), and drainage (D) (Loomis, 1983):

$$W = P + I + S - R - D$$

The storage terms relate only to the portion of soil moisture available to the plant. The field capacity and the wilting coefficient or permanent wilting point are the practical upper and lower

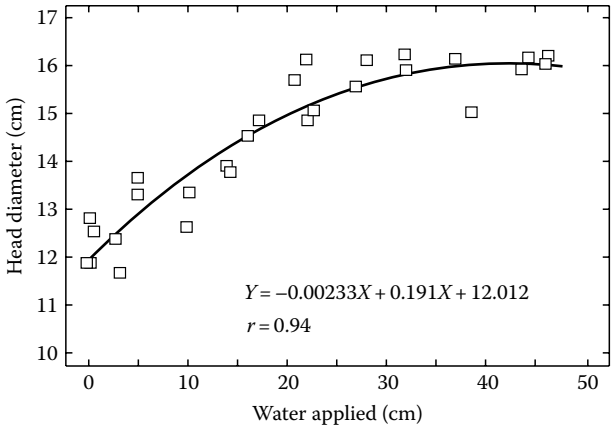

FIGURE 2.4 Relationship of sunflower head size to various amounts of water applied. (From Hang, A.N. and Evans, D.W., *Agron. J.*, 77, 588, 1985. With permission.)

limits of water availability for crops. The upper limit of soil water availability to plants is often considered the water content after saturated soil has freely drained for 2–3 days or wetted soils have been subjected to pressures in the range 5–30 kPa (kilopascals) or 0.05–0.3 bars (Unger et al., 1981). The lower value is generally applicable to light-textured soils and the higher value to heavy-textured soils.

Plants vary widely in the efficiency of water use. The ratio of dry matter production to the amount of water transpired by a crop is known as water-use efficiency. Generally, C_4 plants are about twice as efficient as C_3 plants in utilizing water. The efficient use of available water by these plants is due to a slightly higher stomatal resistance to gas exchange through the C_4 pathway of photosynthesis (Edwards et al., 1983).

Drought stress is often severe in semiarid and arid regions because of long rainless periods and limited soil water storage. However, water stress may also occur in subhumid and humid regions due to short-term drought. The distribution as well as the quantity of rainfall is important. Sometimes, a region has plenty of rainfall but, due to the erratic distribution of the rainfall, crop failure is not uncommon. For example, in the central part of Brazil, the average rainfall is about 1500 mm year^{-1}, sufficient to produce at least two crops if evenly distributed. But 2–3 weeks of drought is very common during the rainy season. These short droughts sometimes result in complete crop failure (Fageria, 1980). Figure 2.5 shows the yield of upland rice in the region with increasing levels of P. It is clear from the figure that during a year with normal rainfall distribution, a yield of about 5 Mg ha^{-1} was obtained at 66 kg P ha^{-1}. But for crops affected with drought for 40 days from the initiation of the floral primordia to flowering, the yield was reduced by about 90%. Most field crops are more sensitive to water stress during the reproduction and grain-filling stages than in the vegetative stage (Fageria, 1980). In cereals, the most sensitive growth stage for water deficiency is around flowering (Yoshida, 1972; Fageria, 2007, 2009).

2.2.1.3 Solar Radiation

Solar radiation is an important climatic factor in plant growth and development (Kiniry et al., 1989; Sinclair and Horie, 1989; Sinclair and Muchow, 1999). The intensity of solar radiation (usually expressed as joules per square meter per unit time, J m^{-2}, or calories per square centimeter per unit time, cal cm^{-2}) varies with the latitude and the season. At the equator, day and night are of almost equal lengths throughout the year. The greatest annual inputs of solar radiation occur in subtropical regions at 20°–30° latitude under climates with little cloud cover and correspondingly low rainfall. In humid tropical regions without prolonged dry seasons, there is comparatively little seasonal variation in energy input, and a steady value of 400–500 cal cm^{-2} day^{-1} is often experienced

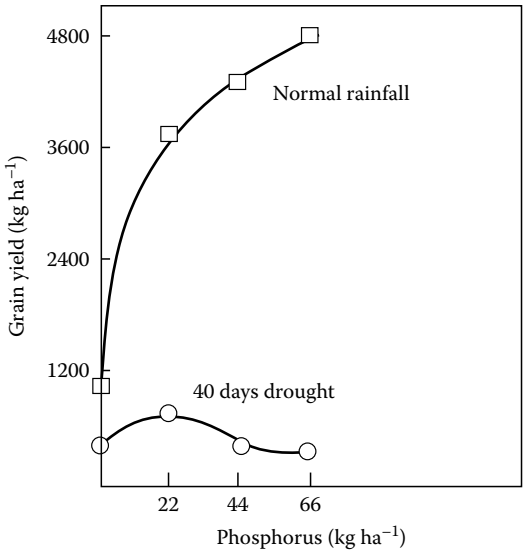

FIGURE 2.5 Upland rice yield influenced by phosphorus and rainfall in the Oxisol of Central Brazil. (From Fageria, N.K., *Pesq. Agropec. Bras.,* 15, 259, 1980.)

(Cooper, 1970). In the tropics and subtropics the net assimilation rate and the relative growth rate can greatly exceed those recorded for cool regions, and these differences are attributed to higher insolation and temperature (Blackman and Black, 1959).

Solar radiation affects photosynthesis and consequently crop productivity. At the upper boundary of the atmosphere, and at the earth's mean distance from the sun, the total irradiance is 1360 J m^{-2} s^{-1}, which includes ultraviolet and infrared wavelengths (Salisbury and Ross, 1985). As radiation passes through the atmosphere to the earth's surface, much energy is lost by absorption and scattering caused by water vapor, dust, CO_2, and ozone. Approximately 900 J m^{-2} s^{-1} reaches plants, depending on the latitude, the time of day, the elevation, and other factors (Salisbury and Ross, 1985). About half of the radiation is in the infrared region of the light spectrum, roughly 5% is in the ultraviolet, and the rest, approximately 400 J m^{-2} s^{-1}, is at wavelengths between 400 and 700 nm, which are capable of causing photosynthesis. This is called photosynthetically active radiation (McCree, 1981).

Dry matter accumulation can be considered as the product of the amount of photosynthetically active radiation absorbed (PAR_A) and the efficiency with which it is used (Monteith, 1977). The amount of radiation absorbed depends on the canopy size often expressed as the leaf area index (LAI, m^2 of leaf area per m^2 of soil surface area) and the radiation extinction coefficient (k). PAR_A is related to the leaf area index (LAI) and k via Beer's law (Goyne et al., 1993):

$$PAR_A = PAR_0\,[1 - \exp(-k\,LAI)]$$

where PAR_0 is the above-canopy or incident radiation.

Dry matter accumulation and PAR_A are often linearly related when soil moisture, nutrients, temperatures, and the number of active growing points do not limit dry matter accumulation (Gallagher and Biscoe, 1978). The slope of this linear relationship is referred to as radiation-use efficiency (RUE) (Stockle and Kiniry, 1990). In reviewing factors affecting cereal yield, Green (1984) concluded that RUE was a relatively stable parameter and that most variations in biomass production were due to changes in the amount of radiation intercepted. Table 2.2 shows the growth rate and the percent utilization of photosynthetically active radiation (PAR) by different crops. It is clear from the data in Table 2.2 that crop growth rate is directly related to total radiation input and only about

TABLE 2.2
Maximum Growth Rate and Solar Energy Utilization by Some Crops

Crop	Location	Growth Rate ($g\ m^{-2}\ day^{-1}$)	Total Radiation Input ($cal\ cm^{-2}\ day^{-1}$)	Percent Utilization of PAR[a] ($cal\ cm^{-2}\ day^{-1}$)	Reference
Barley	The United Kingdom	23	484	4.3	Blackman and Black (1959)
Barley	The Netherlands	17.7	450	3.7	Sibma (1968)
Wheat	The Netherlands	17.5	450	3.7	Sibma (1968)
Corn	The Netherlands	17.1	350	4.6	Sibma (1968)
Corn	Ithaca, New York	52	500	9.8	Wright and Lemon (1966)
Corn	Davis, California	52	736	6.4	Williams et al. (1968)
Corn	New Zealand	29.2	450	6.1	Brougham (1960)
Sorghum	Davis, California	51	690	6.7	Loomis and Williams (1963)
Potato	The Netherlands	23	400	5.4	Sibma (1968)
Pearl millet	Australia	54	510	9.5	Begg (1965)

[a] PAR = photosynthetically active radiation, 400–700 nm.

TABLE 2.3
Estimated Annual Energy Input and Potential Conversion in Different Climates

Climate	Location	Input of Total Radiation ($kcal\ cm^{-2}\ year^{-1}$)	Dry Matter from 3% Conversion of Incoming Light[a] ($Mg\ ha^{-1}\ year^{-1}$)
Tropical	Puerto Rico	160	51
	Singapore	155	49
	Lagos, Nigeria	130	41
	Townsville, Australia	180	57
	Hawaii	155	49
Subtropical	Algiers	165	52
	Davis, California	160	51
	Buenos Aires, Argentina	145	46
	Brisbane, Australia	170	54
Temperate	Wageningen, the Netherlands	90	29
	Wellington, New Zealand	115	37
	Wisconsin	120	38

Source: Compiled from Cooper, J.P., *Herb. Abstr.*, 40, 1, 1970.

[a] Assuming 1 g DM = 4250 cal.

4%–10% of the PAR is utilized in the process of photosynthesis. Solar radiation is higher in tropical and subtropical climates than in temperate climates. Similarly, dry matter production is higher in tropical and subtropical climates than in temperate ones. Table 2.3 shows how much dry matter could be accumulated in different climatic zones if 3% of the incoming solar radiation is converted to dry matter.

In temperate as well as tropical plant species, there are differences in the light saturation level, and hence in maximum photosynthesis. An appreciable variation in the maximum photosynthetic

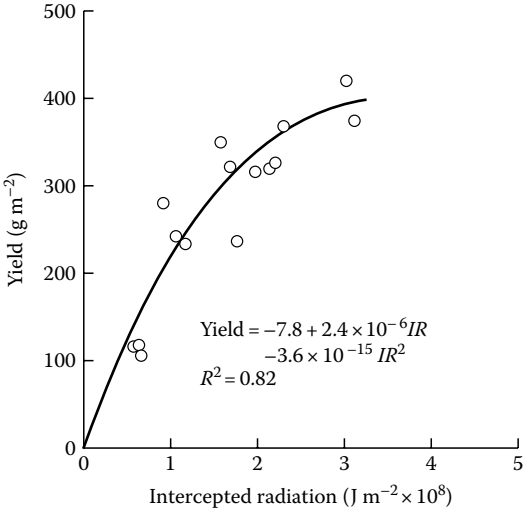

FIGURE 2.6 Yield of barley as a function of intercepted radiation at the grain-filling stage. (From Whiteman, C.E. et al., *Agron. J.*, 77, 663, 1985. With permission.)

rate occurs between varieties and even between individual genotypes, and is often associated with differences in the leaf mesophyll structure or in the activity of the carboxylating enzymes. In some grasses with C_4 photosynthetic metabolism, such as corn and sugarcane, photosynthetic rates continue to increase in response to light intensities up to maximum values of over 70 mg CO_2 dm^{-2} ha^{-1}, equivalent to conversion rates of 5%–6% of the intercepted solar radiation at high light intensities (Hesketh and Moss, 1963). For most tropical grasses, the production of 1 g of dry matter corresponds to the fixation of about 4130–5020 cal of chemically bound energy, and for most temperate grasses it corresponds to 4250 cal (Golley, 1961; Butterworth, 1964).

The relationships between light interception and biomass accumulation apply when other environmental factors such as temperature, soil water contents, soil fertility and disease, and insect pressures do not limit plant growth. When intercepted light is the principal limitation to crop growth rate, the rate is said to be "source limited." However, dry matter accumulation of cereal and legume crops during the grain-filling period can also be limited by the number of seeds available to accumulate dry matter. For example, if drought, disease, or insects reduce the number of viable grains, the rate of plant biomass accumulation during grain filling may be limited by the number of grains available to grow. In such cases, the growth of the crop is said to be "sink-limited." Figure 2.6 shows the relationship between the intercepted solar radiation and the grain yield of barley during grain filling. In this study, the grain yield increased almost linearly with the increasing intercepted solar radiation up to a grain yield of approximately 250 g m^{-2}, suggesting that at the lower part of the curve, grain yield is source-limited. For grain yields above 300 g m^{-2} yields, the curve was flatter, suggesting that at these yield levels, the crop was sink-limited. Alternatively, soil fertility may have been adequate to produce the lesser yields, but became the limiting factor at higher yield levels. In many cases, the limiting factors for grain production can be deduced after harvest by analyzing the number of seeds, the weight of each seed, and the concentration of nutrients in the grain and the crop residues.

2.2.2 Soil

Soil is the unconsolidated mineral material on the immediate surface of the earth that serves as a natural medium for plant growth. Better yield of crops can be expected only when conditions are optimal or favorable in the growth medium. Optimal conditions for plant growth are difficult to

define because they vary with plant species, type of soil, and agroclimatic region. Some conditions or factors that affect plant growth can be related to the soil physical, chemical, and biological properties. These factors, directly or indirectly, affect plant root growth, the absorption of water and nutrients, and consequently, plant growth and yields. How these factors affect plant growth is discussed in this section.

2.2.2.1 Physical Properties

Physical properties are the characteristics, processes, or reactions of soil that are caused by physical forces and that can be described by or expressed in physical or chemical equations. Soil physical properties play an important role in the growth and the development of plants. The important soil physical properties that affect plant growth are texture, structure, consistency, pore space and density, soil tilth, and soil color. These physical properties are interrelated, and a change in one may cause a change in others that may be favorable or adverse. The creation of favorable soil physical conditions for plant growth is a very complex phenomenon.

2.2.2.1.1 Texture

Soil texture refers to the relative proportions of various soil separates, such as sand, silt, and clay in soil. Most soils are mixtures of particles of various sizes. To facilitate the description of these mixtures, classes have been defined according to relative proportions of sand, silt, and clay. The most common classification used in agriculture is that given by the U.S. Department of Agriculture (USDA) (Soil Survey Staff, 1951). According to this classification, soil material that contains 85% or more of sand and a percentage of silt plus 1.5 times clay that does not exceed 15% is known as sand. Silt is the soil material that contains 85% or more silt and less than 12% clay. Clay is the soil material that contains 40% or more clay, less than 45% sand, and less than 40% silt. Sand separates have diameters of 0.05–2 mm, silt 0.05–0.002 mm, and clay less than 0.002 mm. Particles greater than 2 mm in diameter are known as coarse fragments.

Soil texture affects the productivity of crops in several ways. It affects the water-holding capacity of the soil, the aeration, the temperature, the cation exchange capacity (CEC), the nutrient-supplying power, and hence growth and production. The general tendency is for productivity to be better on medium-textured soils than on soils that are either light (sandy) or heavy (clayey). Soil texture is a relatively permanent soil property and is little influenced by tillage or other manipulations unless the modification is drastic. It can be altered by soil loss through erosion or by deposition of new materials from wind or water.

2.2.2.1.2 Structure

The binding of soil particles into aggregates results in structure. Soil structure, in combination with texture, governs the porosity of the soil and thus affects aeration, water infiltration, root penetration, and micro-biological activities of soil flora and fauna. The primary factors in the development of soil structure are the shrink and the swell phenomena during wetting and drying. Pressure is also exerted by plant roots. Soil separates are bonded together by clays, iron, aluminum compounds, and organic substances, such as humus, polyuronides, polysaccharides, and proteins (Baver et al., 1972). Soil structure plays an important role in plant growth, and consequently, in crop production. Soil must have a favorable structure for high productivity. A good soil structure provides adequate aeration and drainage, sufficient water-storage capacity, good root growth, and access to nutrients (Russell, 1973). However, no one structure is completely ideal because requirements differ among crop plants. Moreover, crops will generally grow satisfactorily over a range of structural conditions (Low, 1979). Soil structure can be modified much more readily through cultural practices than can texture.

Soil structure can be extremely important to root growth in fine-textured soils, but soil strength usually is more important than soil structure in sandy soils. Soil strength is defined as the ability or the capacity of a particular soil in a particular condition to resist or to endure an applied force (Gill and Vandenberg, 1967).

2.2.2.1.3 Consistency

Soil consistency is the degree of cohesion or adhesion of the soil mass. Cohesion and adhesion, which are surface phenomena, are largely a function of the clay or organic matter contents in soil and the structural state of soil. The importance of soil consistency in agriculture is related to the stability of the soil structure, the suitability of soil for plowing, and its susceptibility to erosion.

2.2.2.1.4 Pore Space and Density

Pore space is the total space of soil not occupied by soil particles, whereas density is the mass per unit volume including pore space. Soil density, which includes pore space, is known as bulk density. If the mass of a soil, as determined by weighing, is divided by the measured volume of the solids making up the soil, a value expressing the density of the solids or the particle density is obtained (Hausenbuiller, 1972). Soil structure, to a large extent, determines the bulk density of a soil. As a rule, the higher the bulk density, the more compact the soil, the more poorly defined the structure, and the smaller the amount of pore space. Bulk density is really a measure of pore space in the soil. The higher the bulk density for a given textural class, the smaller the amount of pore space present. Particle density varies widely, but the types of particles most prevalent in most soils have density values in the range of 2.6–2.7 g cm^{-3}, with an average of about 2.65 g cm^{-3}. Information on particle density is needed for estimates of porosity, air-filled voids, settling rates of particles in fluids, and transport of particles by wind or water. If the bulk density and the particle density are known, the porosity of a soil can be calculated from the formula

$$\text{Porosity } (\%) = \left(1 - \frac{\text{Bd}}{\text{Pd}}\right) \times 100$$

where

Bd stands for bulk density
Pd for particle density

Soil porosity and bulk density are inversely related. Therefore, any practice that affects one also affects the other. Differences in optimum porosity exist, but values reported in literature are 6%–10% for sudangrass, 10%–15% for wheat and oats, and 15%–20% for barley and sugar beet (Grable, 1966).

High soil strength and bulk density can confine crop root growth (Laboski et al., 1998), alter root distribution (Kaspar et al., 1991), and results in a shallower root system (Oussible et al., 1992). When soil compaction suppresses total root length, shoot growth may also be reduced (Montagu et al., 2001). On clay soils, a single compaction by heavy field traffic can reduce yields and the N uptake of crops for several years (Alakukku and Elonen, 1995). High soil bulk density can decrease the nodulation of soybean plants and subsequently the yield and the protein content of seeds (Katoch et al., 1983). Sweeney et al. (2006) reported that the sorghum yield was reduced with soil compaction or increasing soil bulk density.

2.2.2.1.5 Tilth

Tilth describes the physical condition of soil as related to its ease of tillage, its fitness as a seedbed, and its impedance to seedling emergence and root penetration. A soil with good tilth usually provides an adequate supply of water and air to plants. Soil structure, particularly the degree of aggregation of primary particles, contributes to tilth. Good tilth is more critical in fine-textured than in coarse-textured soils and is influenced by tillage. The specific objectives of tillage in crop production are (1) to physically loosen soils and break hard pans to facilitate the infiltration of water and air, (2) to improve germination and root development, (3) to reduce large aggregates to a desirable size range, (4) to incorporate crop residues, lime, and fertilizers, and (5) to level the soil to facilitate irrigation, weed control, and planting and harvesting operations.

2.2.2.2 Strategies to Improve Soil Physical Properties

Soil physical properties such as structure, porosity, bulk density, and tilth can be improved through appropriate soil-management practices. Some of these management practices are discussed in this section.

2.2.2.2.1 Maintenance of Organic Matter

The term soil organic matter (SOM) refers to all materials of vegetable and animal origin formed in or added to soils, regardless of the stage of decomposition (Finkl, 1979). Soil organic matter thus includes, the highly decomposed and colloidal soil fraction known as humus, as well as organic residues that have not lost their anatomic structure (Brady and Weil, 2002). In addition, Stevenson (1994) defined the soil organic matter to include the whole of organic matter in soils including litter, light fraction, microbial biomass, water-soluble organics, and stabilized organic matter. Soil organic carbon (SOC) is the C fraction of these pools. Further, stable organic matter or humus corresponds to the Soil Science Society of America (1998) definition of soil organic matter. It is the humus fraction that contributes most to soil properties that is of great importance in crop production. Many important soil properties, including absorption and retention of water, reserves of exchangeable cations, the capacity to supply N, P, and S to growing plants, the stability of soil structure, and the adequacy of aeration, are dependent to some degree on the quantity of the organic matter present (Broadbent, 1965).

Figure 2.7 shows a relationship between organic matter (OM) and cation exchange capacity of soil. The marked effect of organic matter on soil cation exchange capacity (CEC) can be explained by the high CEC of organic matter. The CEC–OM relationship in Figure 2.7 shows that an incremental 1% increase in OM on a dry-weight basis (starting near zero) resulted in a corresponding increase of 1.7 cmol (p^+) kg^{-1} in soil CEC (Kapland and Estes, 1985). Similarly, Figures 2.8 and 2.9 show a relationship between organic matter and soil extractable Zn and Mn. As the soil organic matter content in this soil was increased, there was a linear increase in extractable Zn and Mn. Further, organic matter is the main source of energy for soil microorganisms and interacts with fertilizers, pesticides, and herbicides added to soil.

The organic matter in a soil sample is measured indirectly by determining the organic carbon and by using the factor 1.724 to convert organic C to organic matter. This factor is based on an assumed

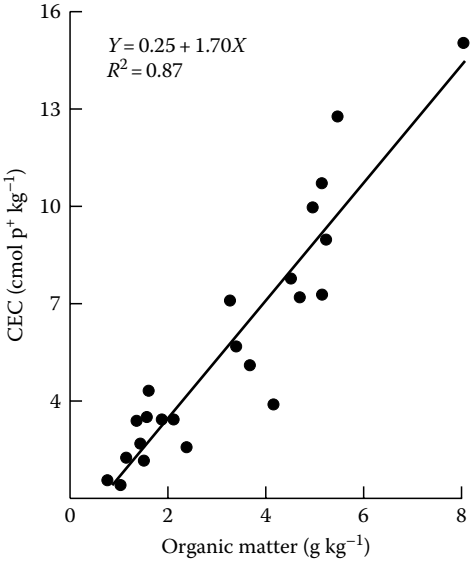

FIGURE 2.7 Relationship between cation exchange capacity and organic matter. (From Kapland, D.I. and Estes, G.O., *Agron. J.*, 77, 735, 1985. With permission.)

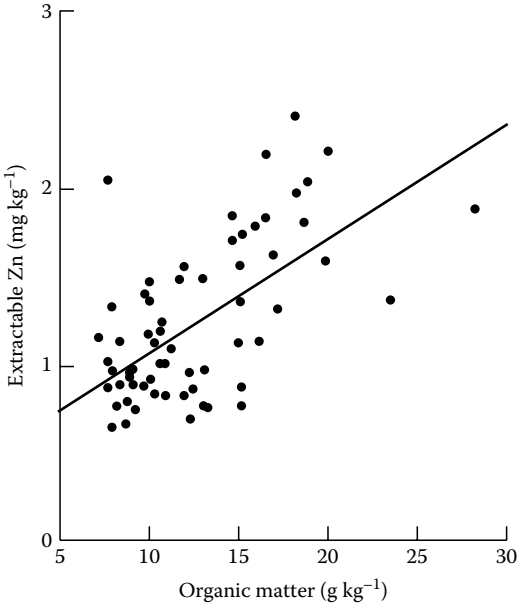

FIGURE 2.8 Relationship between Mehlich-1 extractable Zn and organic matter. (From Kapland, D.I. and Estes, G.O., *Agron. J.*, 77, 735, 1985. With permission.)

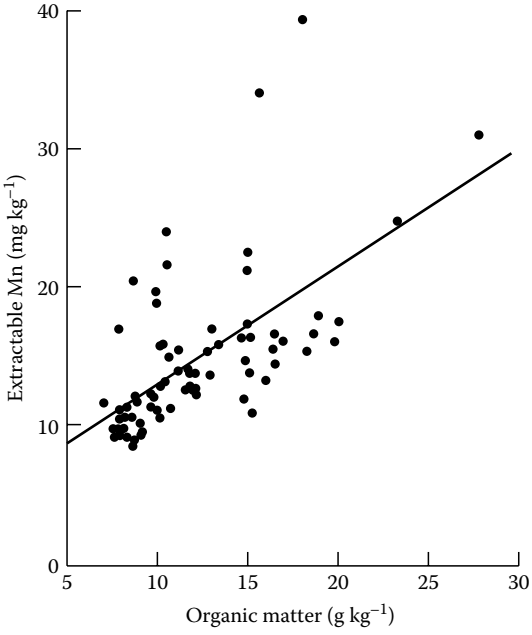

FIGURE 2.9 Relationship between Mehlich-1 extractable Mn and organic matter. (From Kapland, D.I. and Estes, G.O., *Agron. J.*, 77, 735, 1985. With permission.)

C content of 58% for the organic matter (Stevenson, 1986). The numerous combinations under which the soil-forming factors operate account for the great variability in the organic matter contents of soils even in a very localized area. In uncultivated soils, the amount of organic matter present is governed by the soil-forming factors in the following order of importance: climate > vegetation > topography = parent material > age (Jenny, 1930).

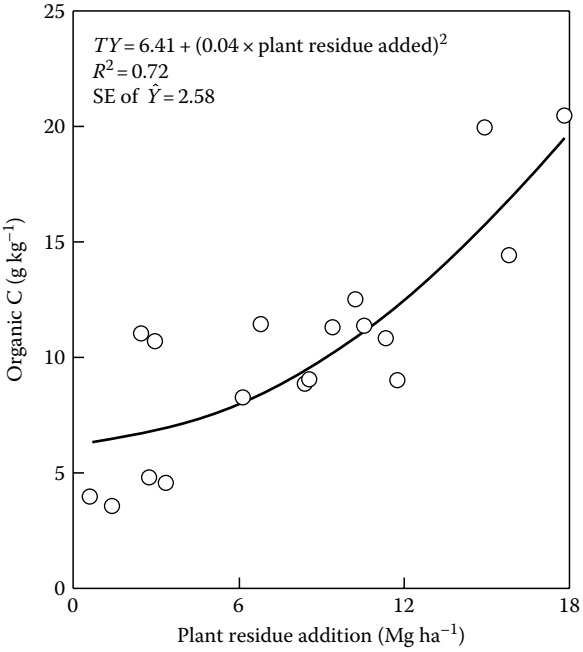

FIGURE 2.10 Relationship between soil organic C concentration in the top 0–5 cm soil layer and plant residue addition. (From Wood et al., *Agron. J.*, 82, 1115, 1990. With permission.)

Absolute amounts of C vary considerably from one soil to another, from less than 1% in some coarse-textured soils (sands) to as much as 3.5% in prairie grassland soils (Stevenson, 1986). Poorly drained soils (aquepts) often have C contents approaching 10%. Soils in warm tropical climates are generally low in organic matter content due to the high activities of microorganisms at the higher temperatures experienced by these soils throughout the year. The organic matter content usually decreases rapidly when soils are brought under cultivation. This is caused by improved aeration and mixing of the plow layer, which increases microbial activity and the decomposition of organic compounds. A net loss of soil organic carbon (20%–60%) was measured in most agricultural land in the first 50 years after conversion from its native prairie or forest state (Janzen et al., 1998; Johnson et al., 2006). In prairie soils, C losses were 17% in the upper landscape position and >70% in the footslope position (Slobodian et al., 2002).

Organic matter in the soil can be maintained or even increased by incorporating crop residues, adding organic manures (animal as well as green plants), keeping the land under pasture and forests, and including a sod crop in the rotation (Lal et al., 1998; Allmaras et al., 2000; Reicosky and Allmaras, 2003; Johnson et al., 2006). Figure 2.10 shows a typical quadratic relationship between plant residue addition and organic C content near the soil surface (0–5 cm).

2.2.2.2.2 Conservation Tillage

Tillage is defined as the mechanical manipulation of soil for crop production. Soil tillage is perhaps as old as settled agriculture, yet its impacts on soil degradation, soil resilience, ecological stability, environmental quality, and agricultural sustainability are more important now than ever before. Properly used, tillage can be an important restorative tool that can alleviate soil-related constraints to crop production. When improperly used, tillage can set in motion a wide range of degradative processes such as deterioration in soil structure, accelerated erosion, depletion of soil organic matter and fertility, and disruption in cycles of H_2O, C, and essential plant nutrients (Lal, 1993). Further, Lal (2004) points out the need to use conservation tillage systems on croplands to enhance soil organic carbon (SOC) storage and to reduce total greenhouse gas emissions from agricultural lands.

Conservation tillage has been defined as any tillage sequence that reduces loss of soil water relative to conventional tillage (Papendick and Elliott, 1983; Tolk et al., 1999). In addition, the definition adopted by the Conservation Technology Information Center (CTIC) is commonly used. The CTIC (1992) defined conservation tillage as "any tillage and planting systems that maintain at least 30% of the soil surface covered by residue after planting to reduce water erosion; or where soil erosion by wind is a primary concern, maintain at least 455 kg of flat, small grain residue equivalent on the surface during the critical wind erosion period." Conservation tillage systems normally involve fewer tillage operations and less energy use for tillage per crop cycle, less incorporation of crop residues into the soil, and an increased reliance on herbicides for weed control. The main outcomes of conservation tillage are increased soil surface roughness and the maintenance of crop residues on the soil surface. In comparison with traditional tillage systems, conservation tillage normally results in less evaporation of water from the soil surface, reduced near-surface soil temperatures, reduced wind and water erosion, and reduced energy use (Unger and McCalla, 1980; Halvorson et al., 2000; Tarkalson et al., 2006). Problems are often encountered with a slower warming of the soil in temperate climates, a poor germination of seeds, and the slow growth of seedlings. The success of conservation tillage systems depends on the soil type, the drainage, the climate, and management practices (Papendick and Elliott, 1983). The development of crop cultivars specially adapted to conservation tillage environments may be one way to increase and/or stabilize crop production (Kaspar et al., 1987; Tarkalson et al., 2006).

The agronomic and economic performance of conservation-effective tillage is extremely location-specific. Problems important in semi-arid regions may not be significant in humid tropical areas. Therefore, to be effective, a conservation-effective tillage program needs to be flexible enough to be adapted to a variety of economic, geographic, and land use and related variables (Benites and Ofori, 1993). In Brazil, 27% of cropland (13.4 million ha) are cultivated under the no-tillage system of which about 70.5% is located in the southern region, including the states of Rio Grande do Sul, Santa Catarina, and Paraná (Sá et al., 2001). The no-tillage system is gaining popularity in the central part of Brazil, in recent years. This is happening because of the low cost of crop production and the soil conservation effects of this system.

2.2.2.2.3 Organic Farming

Organic farming means minimizing the use of chemical fertilizers or pesticides in crop production. In organic cropping systems, soluble inorganic fertilizers are not allowed, although some soluble inorganic K fertilizers are permitted under restricted conditions (Torstensson et al., 2006). Nutrient inputs in such systems originate either from various organic sources like animal and green manures or from naturally occurring minerals with very low solubility like P apatite. Other features related to the use of nutrients in organic cropping systems include the enhancement and the improvement of the biological conditions for symbiotic N_2 fixation (Torstensson et al., 2006). In addition, special emphasis is given on the recycling of animal manures, and the creation of a balance between the number of animals and the cultivated area for crops (Kirchmann and Bergstrom, 2001).

In this type of farming, farmers maintain the top soil in good physical condition through a regular use of soil-building cover crops. Weeds, insect pests, and plant diseases are kept in check through the use of crop rotation, timely tillage, and biological controls. Several thousand farmers in the United States are operating commercial farms profitably with organic farming since the early 1980s (Papendick and Elliott, 1983).

Organic farming has since grown in popularity in the European Union (EU) and the United States. In 2005, the area devoted to organic agriculture in the EU was 3.9% of the total area used for agriculture, with the highest proportions in Austria (11.0%), Italy (8.4%), the Czech Republic and Greece (both 7.2%) (http://ec.europa.eu/agriculture/organic/home_en, December 29, 2008). Certified organic farming has also increased in the United States, but in 2005, certified organic production was in use on only about 0.5% of all U.S. croplands. Obstacles to the adoption of organic

production systems include high managerial costs, risks and costs associated with shifting to a new way of farming, limited awareness of organic farming systems, and a lack of marketing techniques and infrastructure. Nevertheless, farmers who have made the transition to organic systems have done so to lower input costs, to conserve nonrenewable resources, to capture high-value markets, and to boost farm income (http://www.ers.usda.gov/Briefing/Organic, December 28, 2008).

2.2.2.3 Soil Chemical Properties

Soil chemical properties such as nutrient deficiencies and toxicities, pH, the cation exchange capacity, oxidation–reduction, and salinity are important soil properties affecting the growth and the production of crops. These soil properties can be modified through management practices for higher crop production. At present, sufficient know-how is available throughout most of the world to improve unfavorable soil chemical properties. But for economic reasons, it is often not possible to apply this knowledge in a particular situation. A new and improved technology will normally be adopted by farmers if it helps them meet their goals, which usually include increasing profits and reducing risks. The belief that farmers are hesitant to adopt new technologies is outdated. This has been proved by the adoption by resource-poor Asian farmers of high-yielding wheat and rice cultivars, along with increased fertilizer and pesticide applications needed to take advantage of their higher yield potential.

2.2.2.3.1 Nutrient Deficiencies

Inadequate soil supplies of plant nutrients often restrict plant growth and yield. Nutrient deficiencies vary among soils and areas (Table 2.4), but nitrogen and phosphorus are the most frequently deficient nutrients in temperate as well as tropical soils all around the world. Among the essential nutrients, potassium is the nutrient that is absorbed in greatest amounts by modern improved crop cultivars. The nutrient deficiencies in a particular soil are related to parent material, weathering, cultivation, past fertilizer and cropping practices, and erosion. Modern cultivars require a higher rate of nutrients due to higher grain yields compared to old cultivars (Ladha and Reddy, 2003; Samonte et al., 2006).

The nutrient-supplying power of a soil is normally evaluated through soil and plant analysis and visual symptoms in plants. But crop response to applied nutrients is the best indicator of the nutritional status of a soil. In such evaluations, all other growth factors should be at optimum levels. Nutrient deficiencies can be alleviated through the application of fertilizers and amendments and the use of cultivars that efficiently absorb and use nutrients.

2.2.2.3.2 Nutrient/Elemental Toxicities

The toxicities most commonly found in food crops are those of aluminum, manganese, and iron. Aluminum and manganese toxicities are most common in acid soils, whereas iron toxicity occurs in flooded rice under reduced soil conditions. Table 2.4 presents common nutrient and elemental toxicities in important soil groups. Crop yield reduction varies with the intensity of the toxicity, and the intensity of the toxicity varies with plant species, soil, and climatic conditions. Figure 2.11 shows that the relative grain yield of Al-susceptible common bean cultivars decreased quadratically with an increasing Al saturation while the yields of Al-tolerant rice cultivars, increased with an increasing Al saturation in an Inceptisol.

Metal toxicity can be expressed in two ways. Direct toxicity occurs when an excess of the element is absorbed and becomes lethal to the plant cell. Indirect toxicity can be related to nutritional imbalance. When excess Al, Mn, and Fe are present in the growth medium, they may inhibit the uptake, the transport, and the utilization of many other nutrients and induce nutritional deficiency. Table 2.5 shows the Al inhibition of nutrient uptake by rice plants grown in a nutrient solution. Increased Al concentrations in the solution exerted an inhibiting effect on the concentrations of N, P, K, Ca, Mg, Zn, Fe, Mn, and Cu in the plant tops. Decreases in the uptake of these elements

TABLE 2.4
Element Deficiencies and Toxicities Associated with Major Soil Groups

		Element	
Soil Order	**Soil Group**	**Deficiency**	**Toxicity**
Andisols (Andepts)	Andosol	P, Ca, Mg, B, Mo	Al
Ultisols	Acrisol	N, P, Ca, and most other	Al, Mn, Fe
Ultisols/Alfisols	Nitosol	P	Mn
Spodosols (Podsols)	Podzol	N, P, K, Ca, micronutrients	Al
Oxisols	Ferralsol	P, Ca, Mg, Mo	Al, Mn, Fe
Histosols	Histosol	Si, Cu	
Entisols (Psamments)	Arenosol	K, Zn, Fe, Cu, Mn	
Entisols (Fluvents)	Fluvisol		Al, Mn, Fe
Mollisols (Aqu), Inceptisols, Entisols, etc. (poorly drained)	Gleysol	Mn	Fe, Mo
Mollisols (Borolls)	Chernozem	Zn, Mn, Fe	
Mollisols (Ustolls)	Kastanozem	K, P, Mn, Cu, Zn	Na
Mollisols (Aridis) (Udolls)	Phaeozem		Mo
Mollisols (Rendolls) (shallow)	Rendzina	P, Zn, Fe, Mn	
Vertisols	Vertisol	N, P, Fe	S
Aridisols	Xerosol	Mg, K, P, Fe, Zn	Na
Aridisols/Arid Entisols	Yermosol	Mg, K, P, Fe, Zn, Co, I	Na, Se
Alfisols/Ultisols (Albic) (poorly drained)	Planosol	Most nutrients	Al
Alfisols/Aridisols/Mollisols (Natric) (high alkali)	Solonetz	K, N, P, Zn, Cu, Mn, Fe	Na
Aridisols (high salt)	Solonchak		B, Na, Cl

Sources: Compiled from Dudal, R., Inventory of the major soils of the world with special reference to mineral stress hazards, in *Plant Adaptation to Mineral Stress in Problem Soils*, *Proceedings of a Workshop*, National Agricultural Library, Beltsville, MD, Wright, M.J. (ed.), Special Publication of Cornell University Press, Ithaca, NY, 3–13, 1976; Clark, R.B., Plant response to mineral element toxicity and deficiency, in *Breeding Plants for Less Favorable Environments*, Christiansen, M.N. and Levis, C.F. (eds.), Wiley, New York, 71–142, 1982.

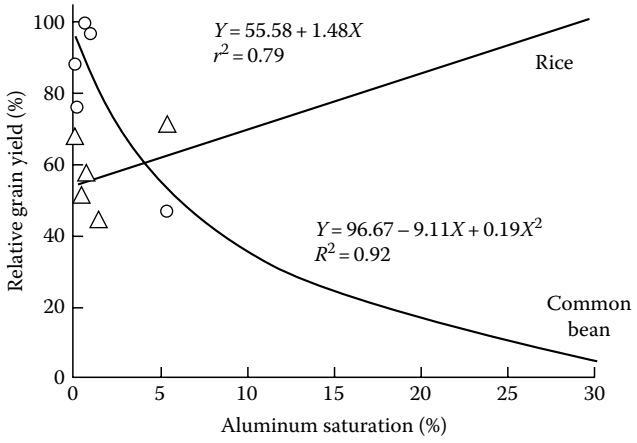

FIGURE 2.11 Relationship between aluminum saturation and relative grain yield of rice and common bean in an Inceptisol. (From Fageria, N.K. and Santos, A.B., Rice and common bean growth and nutrient uptake as influenced by aluminum on a Varzea soil, in *Paper Presented at IV International Symposium on Plant-Soil Interactions at Low pH*, Belo Horizonte, Brazil, March 17–24, 1996.)

TABLE 2.5
Influence of Al on Uptake of Nutrients by Rice Plants at a 21 Day Growth in Nutrient Solution[a]

	Al Concentration (μm)				
Nutrient	**0**	**371**	**742**	**1484**	**2226**
N	50.0	44.9	47.6	45.0	41.5
P	6.2	5.1	4.9	3.6	3.3
K	44.4	41.8	39.9	32.8	26.5
Ca	2.0	1.9	1.8	1.5	1.4
Mg	3.8	2.7	2.6	2.6	2.4
Zn	31	26	23	18	12
Fe	299	297	237	172	176
Mn	695	505	449	276	146
Cu	21	24	22	18	18

Source: Compiled from Fageria, N.K. and Carvalho, J.R.P., *Plant Soil*, 69, 31, 1982.

[a] Values are means for six cultivars. Concentrations of macronutrients are in g kg^{-1}, and of micronutrients in mg kg^{-1}.

were mostly related to the morphological, physiological, and biochemical effects of Al (Fageria and Carvalho, 1982; Fageria et al., 1988; Fageria, 2009). These effects can be explained by the following hypotheses:

1. Aluminum inhibits root growth, thereby causing the uptake of these nutrients to be reduced (Fageria, 1982).
2. Aluminum reduces cellular respiration in plants, inhibiting the uptake of all ions (Aimi and Murakami, 1964).
3. Aluminum increases the viscosity of protoplasm in plant root cells and decreases the overall permeability to salts (McLean and Gilbert, 1927; Aimi and Murakami, 1964).
4. Aluminum blocks, neutralizes, or reverses the negative charges on the pores of the free space and thereby reduces the abilities of such pores to bind Ca (Clarkson, 1971).
5. Aluminum may compete for common binding sites at or near the root surface and thereby reduce the uptake of K, Ca, Mg, and Cu (Harward et al., 1955; Hiatt et al., 1963).
6. Aluminum reduces Ca uptake by completely inactivating part of the Ca accumulation mechanism (Johnson and Jackson, 1964).
7. In general, aluminum interferes with cell division in plant roots, decreases root respiration, interferes with certain enzymes governing the deposition of polysaccharides in cell walls, increases cell wall rigidity, and interferes with the uptake, the transport, and the use of several elements such as K, Ca, and Mg (Foy, 1974).
8. Aluminum injures plant roots and reduces Ca uptake (Lance and Pearson, 1969).
9. Aluminum decreases the sugar content, increases the ratio of nonprotein to protein N, and decreases the P contents of leaves from several plants grown on acid soils (Foy, 1974).

Similarly, high Fe concentrations in the growth medium reduced the uptake of nutrients (Table 2.6). Among macronutrients, the uptake of P was highly affected, followed by K and N. Among micronutrients, the absorption of Mn and Zn were most affected. These results suggest that when there is a higher concentration of Fe in lowland or flooded rice it can induce, P, K, and Zn deficiencies,

TABLE 2.6
Uptake of Nutrients in the Roots and Shoots of Rice Cultivars[a]

	Iron Concentration (mM)					
	0.09		0.89		1.73	
Nutrients	Concentration (g kg^{-1} or mg kg^{-1})	Content (mg or µg per 4 plants)	Concentration (g kg^{-1} or mg kg^{-1})	Content (mg or µg per 4 plants)	Concentration (g kg^{-1} or mg kg^{-1})	Content (mg or µg per 4 plants)
Roots						
N	28.2	23	27.6	11	25.3	6
P	3.3	2.66	2.7	1	3.9	0.96
K	29.5	25	17.3	6	14.6	4
Ca	0.8	0.65	1.0	0.38	1.1	0.26
Mg	1.2	1	1.1	0.42	1.1	0.26
Zn	44	37	26	10	38	10
Cu	19	15	22	8	23	6
Mn	22	18	27	10	38	9
Fe	2,258	1,806	12,717	4,658	37,458	9,202
Shoots						
N	40.9	186	33.8	51	41.8	50
P	4.8	21	1.8	3	2.6	3
K	29.5	133	19.4	26	21.7	25
Ca	1.7	8	2.4	3	2.2	3
Mg	4.3	19	3.9	5	2.2	5
Zn	24	109	18	24	21	25
Cu	14	62	16	22	17	20
Mn	199	874	139	183	152	184
Fe	350	1,578	2,008	2,627	4,233	4,988

[a] Values are the mean for 12 cultivars. Concentrations of macronutrients are in g kg^{-1} and of micronutrients in mg kg^{-1}. Similarly, macronutrient contents are in mg and micronutrient contents in µg.

if concentrations of these nutrients in the soil are not sufficiently high. One way to solve the iron toxicity problem in lowland rice is to increase P, K, and Zn supplies through fertilization.

2.2.2.3.3 pH

Soil pH is one of the most important soil chemical properties (Fageria, 2008). Soil pH can signal the need for lime, the likelihood of excess phytotoxic ions, the activity of microorganisms, and the relative availability of most inorganic nutrients. The pH indicates whether a soil is acid, neutral, or alkaline. Neutrality occurs at a pH of 7.0. Acidity is associated with any pH value less than 7.0 and alkalinity with any value above 7.0. At pH 7.0, the concentration of H^+ ions and OH^- ions are equal. In alkaline soils OH^- concentrations exceed those of H^+, whereas in acid systems the reverse is true. The pH values of most agricultural soils are in the range of 4–9. For acid soils, the most useful soil pH is the minimum pH above which liming will not increase crop yield. This is sometimes called the "critical" pH (Adams, 1981). Critical soil pH values for various crops are given in Table 2.7. These values should be used with caution because critical pH will vary with soil type and among cultivars of the same species.

The amount of lime required to raise the pH of an acid soil to a specific value is determined by the soil's pH buffer capacity and is directly proportional to the cation exchange capacity of highly weathered soils (Adams, 1981). At a low base saturation and a low pH, soil pH values are

TABLE 2.7
Critical Soil pH for Important Crops and Their Classification to Soil Acidity

Crop	Critical Soil pH	Classification
Alfalfa (*Medicago sativa* L.)	6.0–6.5	Susceptible
Red clover (*Trifolium pratense* L.)	6.0–6.5	Susceptible
Sugar beet (*Beta vulgaris* L.)	6.0–6.5	Susceptible
Barley (*Hordeum vulgare* L.)	5.5–6.0	Moderately tolerant
Cotton (*Gossypium hirsutum* L.)	5.5–6.0	Moderately tolerant
Sorghum (*Sorghum vulgare* Pers.)	5.5–6.0	Moderately tolerant
Soybean (*Glycine max* L. Merr.)	5.5–6.0	Moderately tolerant
Wheat (*Triticum aestivum* L.)	5.5–6.0	Moderately tolerant
Common bean (*Phaseolus vulgaris* L.)	5.5–6.0	Moderately tolerant
Corn (*Zea mays* L.)	5.0–5.5	Tolerant
Oats (*Avena sativa* L.)	5.0–5.5	Tolerant
Peanuts (*Arachis hypogaea* L.)	5.0–5.5	Tolerant
Potato (*Solanum tuberosum* L.)	5.0–5.5	Tolerant
Rice (*Oryza sativa* L.)	5.0–5.5	Tolerant

Sources: Compiled from Adams, F., Alleviating chemical toxicities: Liming acid soils, in *Modifying the Root Environment to Reduce Crop Stress* (Monograph 4), Arkin, G.F. and Taylor, H.M. (eds.), American Society of Agricultural Engineers, St. Joseph, MI, 269–301, 1981; Fageria, N.K., *Tropical Soils and Physiological Aspects of Crops*, EMBRAPA, Belem, Brazil, 1989.

highly buffered because of the hydrolytic reactions of Al^{3+}, after it has exchanged for Ca^{2+} or Mg^{2+}, according to the reaction (Adams, 1981)

$$Al^{3+} + 3H_2O = Al(OH)_3 + 3H^+$$

For soils low in organic matter, the amount of lime required to change soil pH by one unit is the least in the pH range of about 5–6 where exchangeable Al^{3+} is nil and the HCO_3^- system is insignificant. Soil scientists have long recommended that acid soils be limed to pH values between 6.0 and 7.0. For example, Lathwell and Reid (1984) reported that adequate soil pH for maximum grain yield for annual crops is in the range of 6.0–7.0. Alley and Zelanzy (1987) also reported that acid soils should be limed to raise their pH to around 6.5. These authors also reported that a soil pH around 6.5 favors the growth of annual crops. However, the optimum pH for crop growth can vary among crop cultivars and soils. For example, Howeler (1980) reported that the optimal soil pH for dry bean varied from 6.5 to 7.5 depending on the soil type and the cultivar planted. Fageria (2001) reported an adequate soil pH of 6.2 for dry bean grain yield in the conventional planting system. However, Fageria (2008) reported that optimal soil pH for dry bean was 6.5 in the no-tillage system grown on Brazilian Oxisol.

Figure 2.12 shows the relative dry matter yield of tops of corn, soybean, and wheat with increasing soil pH in a Brazilian Inceptisol. Yields of wheat and soybean were significantly ($P < 0.05$) increased in a quadratic response with increasing soil pH from 4.7 to 7.0. The maximum relative dry weight of tops of wheat was achieved at pH 6.3, corn at pH 5.4, and soybean at pH 5.6, as calculated from the quadratic equations. Similarly, data presented in Figure 2.13 show that shoot dry weight and the grain yield of dry bean was significantly influenced by soil pH. A maximum yield of both these parameters was achieved at pH 6.4.

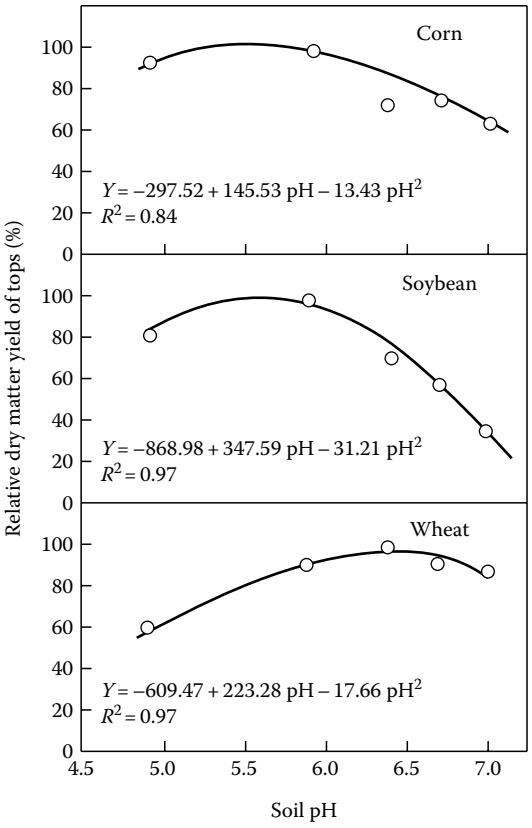

FIGURE 2.12 Relationship between soil pH and the relative dry matter yield of tops of corn, soybean, and wheat in an Inceptisol. (From Fageria, N.K. and Zimmermann, F.J.P., Influence of pH on growth and nutrient uptake by crop species in an Oxisol, in *Paper Presented at IV International Symposium on Plant–Soil Interactions at Low pH*, Belo Horizonte, Brazil, March 17–24, 1996.)

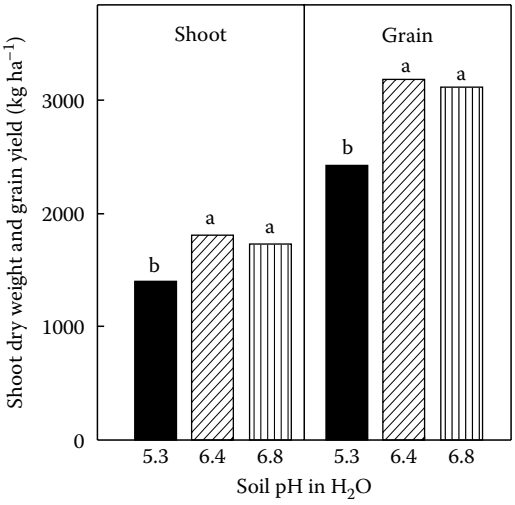

FIGURE 2.13 Influence of soil pH on shoot dry weight and the grain yield of dry bean. (From Fageria, N.K. and Barbosa Filho, M.P., *Commun. Soil Sci. Plant Anal*., 39, 1016, 2008.)

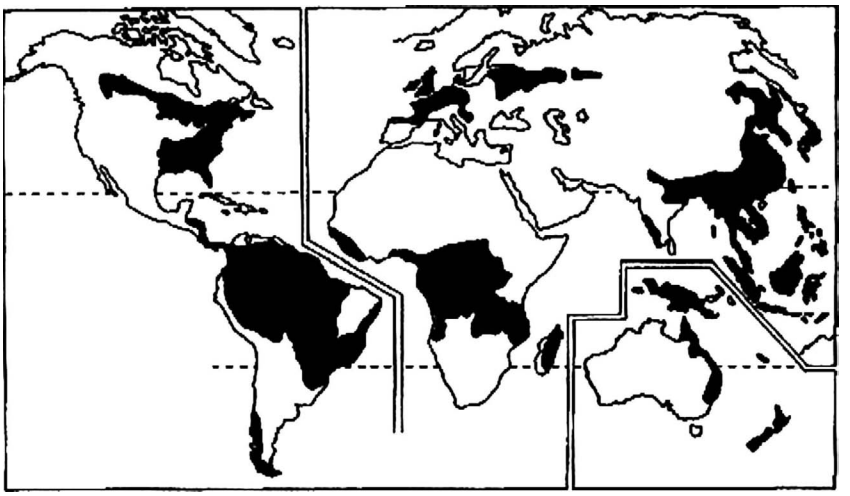

FIGURE 2.14 Distribution of acid soils in climates warmer than cyric. (From Van Wambeke, A., Formation, distribution and consequences of acid soils in agricultural development, in *Plant Adaptation to Mineral Stress in Problem Soils*, *Proceedings of a Workshop*, National Agricultural Library, Beltsville, MD, Wright, M.J. (ed.), Special Publication of Cornell University Press, Ithaca, NY, 15–24, 1976.)

Increases in grain yield with an increasing soil pH is associated with an increasing availability of certain nutrients, especially N, P, Ca, and Mg, as well as a reduction of Al^{3+} toxicity (Fageria and Baligar, 2003; Menzies, 2003). Foy (1984) reported that with increasing H^+ activity in the soil, the solution uptake of P, Ca, and Mg were reduced and Al^{3+} activity increased. Other factors that can contribute to increased yields with increasing pH are improved biological N_2 fixations and a more rapid mineralization of organic matter (Foy, 1984; Menzies, 2003). For example, in plots with pH 5.3, N deficiency was observed 3 weeks after sowing dry bean in Brazilian Oxisol, whereas in plots with pH 6.4 and 6.8 N, deficiency was not observed (Fageria and Barbosa Filho, 2008). This suggests that liming increased the mineralization of organic N and consequently increased N uptake by the crop.

Low soil pH stress is a major growth-limiting factor for crop production in many regions of the world. Figure 2.14 shows the distribution of acid soils in the world. Soil acidity may be due to the parent material being acidic and naturally low in the basic cations such as Ca^{2+}, Mg^{2+}, K^+, and Na^+ or to leaching of these elements down the soil profile by excess rains (Kamprath and Foy, 1971; Fageria and Baligar, 2008). Soil acidity may also be produced by the prolonged use of ammonium fertilizers for a long time, the removal of cations in the harvested portion of crops, and the decomposition of plant residues or organic wastes into organic acids.

2.2.2.3.4 Cation Exchange Capacity

The cation exchange capacity (CEC) is defined as the sum of the exchangeable cations retained by soil. It is expressed in milliequivalents 100 g^{-1} or in cmol of cations kg^{-1} of soil. Cation exchange in soil is a reversible chemical reaction and corresponds to the negative charge of the soil. The cation exchange capacity of soils is highly variable. The principal factors which determine CEC are the amount and the type of clay present, the organic matter content, and the soil pH. Representative CEC values of common exchange materials in soils at pH 7.0 are organic matter 200–400 meq 100 g^{-1}, vermiculite 100–150 meq 100 g^{-1}, montmorillonite 60–100 meq 100 g^{-1}, illite 20–40 meq 100 g^{-1}, kaolinite 2–16 meq 100 g^{-1}, and sesquioxides 0 meq/100 g (Hausenbuiller, 1972). The negative charge, and hence the CEC, increases as pH rises. The capacity of the soil to adsorb exchangeable cations cannot therefore be defined unless a standard pH for its measurement is agreed on (Bache, 1979). The cation exchange capacity is most commonly determined as the

quantity of cations absorbed from the salt solution buffered at pH 7 with NH_4OAc or at pH 8.2 with $BaCl_2$-triethanolamine. For soils with field pH values of 7–8.2, these measurements adequately reflect the CEC. They are also adequate if the soil has little or no variable charge (Sanchez, 1976). But this method is generally not suitable for tropical soils that exhibit a significant amount of variable charge or for temperate soils with significant organic matter contents. The measurement that reflects, more accurately, the total charge at the actual soil pH involves leaching with a neutral, unbuffered salt, such as KCl or $CaCl_2$, determined at the pH of the soil (Sanchez, 1976). Coleman and Thomas (1967) called this CEC, the effective CEC. Cation exchange capacities obtained by this method are generally lower values than those obtained by other methods. A minimum value of 4 cmol kg^{-1} is needed to retain most cations susceptible to leaching. For acid soils, the cation exchange capacity can be increased through the addition of organic matter or lime.

2.2.2.3.5 Base Saturation

Base saturation is an important soil chemical property in acid soils, affecting both nutrient uptake and plant growth. It can be calculated with the help of the following formula (Fageria, 2009):

$$\text{Base saturation} = \sum \left(\frac{\text{Exchangeable Ca, Mg, K, Na}}{\text{CEC at pH 7 or 8.2}} \right) \times 100$$

where

values of exchangeable Ca, Mg, K, and Na should be expressed in $cmol_c\ kg^{-1}$
CEC = Σ(Ca, Mg, K, Na, H, Al) in $cmol_c\ kg^{-1}$

From the standpoint of the soil chemical properties and reactions, base saturation can be considered an acidity index or liming index (Bohn et al., 1979). Figure 2.15 shows the relationship between base saturation and the relative dry matter yields of tops of rice, wheat, corn, common bean, and cowpea grown on an Oxisol in central Brazil. The maximum yield of upland rice was achieved at about 25% base saturation, wheat at about 60%, common bean at about 67%, and cowpea at about 53%, as calculated from the quadratic regression equations. Corn dry matter increased linearly between 26% and 80% base saturation in the soil under investigation.

2.2.2.3.6 Oxidation–Reduction

Oxidation–reduction is a chemical reaction in which electrons are transferred from a donor to an acceptor (Ponnamperuma, 1972). The donor loses electrons and increases its oxidation number or is oxidized; the acceptor gains electrons and decreases its oxidation number or is reduced. The main source of electrons for biological reductions is organic matter. In well-drained soils, oxidation–reduction potentials range from +0.4 to +0.6 V, whereas in waterlogged and submerged soils in the presence of organic substances, reduction processes can decrease the potential to +0.2 V and below (Orlov, 1979). The principal factors controlling the potential level are aeration and the operation of biological processes. Oxidation–reduction changes the concentrations of the nutrients, and hence their availability to plants. Under reduced conditions, Fe^{3+} changes to Fe^{2+} and Mn^{4+} to Mn^{2+}, thus affecting the availability of these nutrients to flooded rice. Sometimes, concentrations of these elements become so high that toxicity occurs.

Root activity alters the rhizosphere redox potential through respiratory oxygen consumption and ion uptake or exudation. In particular, root absorption and the assimilation of NH_4^+ and NO_3^- consume 0.31 mol O_2 mol^{-1} NH_4^+ and 1.5 mol O_2 mol^{-1} NO_3^-, respectively (Bloom et al., 1992). Hence, when roots use NO_3^- as a nitrogen source, the rhizosphere redox potential declines more rapidly than when they use NH_4^+ (Bloom et al., 2003). The concentration of NH_4^+ and NO_3^- in the rhizosphere and the rhizosphere redox potential may be partially responsible for the observed large fluctuations in the relative availability of soil NH_4^+ and NO_3^- and in root growth (Jackson and Bloom, 1990).

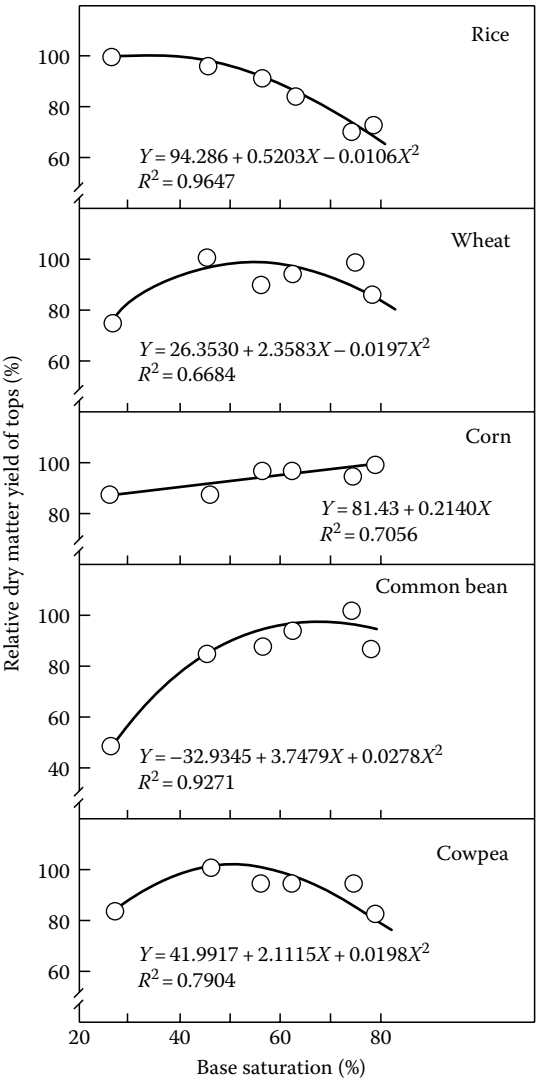

FIGURE 2.15 Relationship between base saturation and the relative dry matter yield of tops of rice, wheat, corn, common bean, and cowpea in an Oxisol.

There are many other nutrient solubility or uptake processes in the rhizosphere that alter the redox potential. Redox reacts with various forms of Mn (Mn^{2+} and Mn^{4+}), Fe (Fe^{2+} and Fe^{3+}), and Cu (Cu^{+} and Cu^{2+}) (Lindsay, 1979). However, the Fe and Mn redox reactions are considerably more important than Cu because of their higher concentrations in soil (Fageria et al., 2002). The primary source of electrons for biological redox reactions in soil is organic matter, but aeration, pH, and root and microbial activities also influence these reactions. Redox reactions in rhizosphere can also be influenced by organic metabolites produced by roots and microorganisms (Fageria and Stone, 2006).

Release of some acids like caffeic and malic from plant roots can also change the redox potential of the rhizosphere (Romheld and Marschner, 1983). Bienfait et al. (1983) reported that the reductant release in the rhizosphere by dry bean plants (*Phaseolus vulgaris* L.) contributed about 14% of the total amount of Fe reduced by roots of Fe-sufficient plants and less than 2% for Fe-deficient plants. It is also reported by Bienfait et al. (1983) and Romheld and Marschner (1983) that root-induced change in the redox potential is likely to be restricted to the root–soil interface and did not extend

into the rhizosphere. Generally, there is a positive correlation between soil oxygen and the redox potential (Bhattarai et al., 2005). Poor soil aeration reduces the active uptake of plant nutrients. For example, uptake rates of N, P, K, Ca, and Mg decreased with reduced aeration (McLaren and Cameron, 1986), for the ATP supplied by anaerobic respiration is not sufficient to provide energy to satisfy the demand for mineral uptake (Barrett-Lennard, 2003).

2.2.2.3.7 Salinity and Alkalinity

A soil containing sufficient quantities of soluble salts and exchangeable sodium to interfere with the growth of most crop plants is known as a saline-sodic soil. Figure 2.16 shows the relative yield of two canola cultivars as a function of increasing soil salinity. The traditional classification of salt affected soils has been based on the soluble salt (EC) concentrations in an extracted soil solution and on the exchangeable sodium percentage of the associated soil. The dividing line between saline and nonsaline soils was established at 4 dS m^{-1} for water extracts from saturated soil pastes. Salt-sensitive plants, however, can be affected in soils whose saturation extracts are only 2–4 dS m^{-1}. The terminology committee of the Soil Science Society of America lowered the boundary between saline and nonsaline soils to 2 dS m^{-1} in the saturation extract (Bohn et al., 1979). In an alkali soil, more than 15% of the cation exchange capacity is saturated with alkali ions, most often sodium. In salt-affected soils, the yield reduction may result from the osmotic stress caused by the total soluble salt concentration, from toxicities or nutrient imbalances created when specific salts become excessive, or from the reduction of water penetration of the soil structure (Hoffman, 1981).

In a salt-affected environment, there is a preponderance of nonessential elements over essential elements. In salt-affected soils, plants must absorb the essential nutrients from a diluted source in the presence of highly concentrated nonessential nutrients. This requires extra energy and plants are sometimes unable to fulfill their nutritional requirements. There are two main stresses imposed by salinity on plant growth. One is the water stress imposed by the increase in the osmotic potential of the rhizosphere as a result of high salt concentration. Another stress is the toxic effect of the high concentration of ions. Hale and Orcutt (1987) reported that if the salt concentration is high enough to lower the water potential by 0.05–0.1 MPa, then the plant is under salt stress. If the salt concentration is not this high, the stress is ion stress and may be caused by one particular species of ion (Hale and Orcutt, 1987).

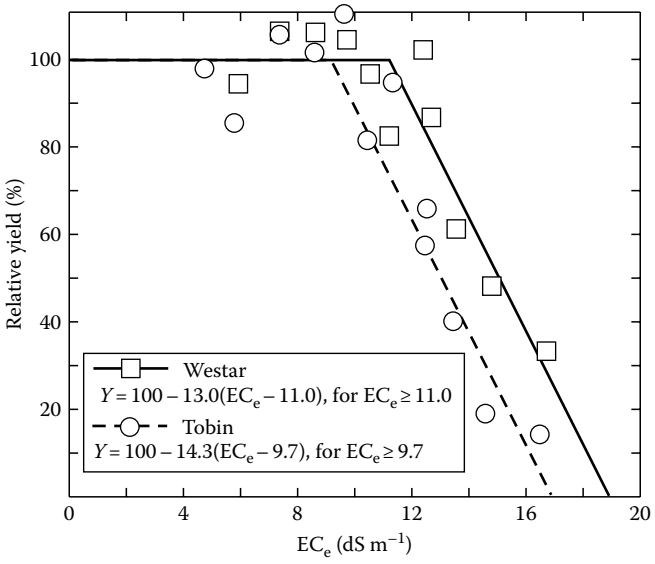

FIGURE 2.16 Relative seed yield of two canola cultivars as a function of increasing soil salinity. (From Francois, L.E., *Agron. J.*, 86, 233, 1994. With permission.)

The bioavailability of nutrients is one of the most important crop production factors, which is significantly influenced by salinity (Grattan and Grieve, 1999). The nutritional disorders on salt-affected soils may be the result of the effect of salinity on nutrient availability, the competitive uptake, the transport or the partitioning within the plant. For example, salinity reduces P uptake and its accumulation in crops grown on salt-affected soils primarily by reducing P availability. Salts dominated by Na^+ not only reduce Ca^{2+} availability but reduce its transport and mobility to the growing regions of the plant, affecting the quality of both vegetative and reproductive organs. Salinity can directly affect nutrient uptake; Na^+ reduces the uptake of K^+ and Cl^- and can reduce the uptake of NO_3^-. Salinity can cause a combination of complex interactions that affect plant metabolism, the susceptibility to injury or the internal nutrient requirement. The negative interactions of salts with crop plants may reduce growth and consequently nutrient use efficiency.

Management practices to correct salinity and alkalinity include irrigation to leach salts below the root zone and the use of tolerant species or cultivars within species. Special care is required in saline-alkali soils, however, because the removal of soluble salts without reducing the exchangeable sodium percentage leads to a highly undesirable soil structure. The sodium saturation percentage can be lowered before leaching through the addition of calcium salts (gypsum) or through the use of acid-forming substances, such as sulfur, H_2SO_4, iron sulfate, and organic matter (Oertli, 1979).

2.2.2.4 Biotic

Biotic factors that affect crop production are related to soil microorganisms, such as bacteria, actinomycetes, fungi, and nematodes. These microorganisms carry out a range of activities in the plant rhizosphere that are harmful, as well as beneficial for plant growth. Table 2.8 lists some of the various impacts that microorganisms around the root have on plant growth. The more common activities are, breakdown of organic matter, nitrogen fixation, secretion of growth substances, and increase in the availability of mineral nutrients. They can also cause plant disease or protect the plant from pathogens.

From the point of view of their relationships with plants, microorganisms can be classified into three groups (Barea and Aguilar, 1983): (1) *saprophytes*, usually opportunists, but benefactors in some situations; (2) *parasitic symbionts* or *pathogens*, potentially harmful to the plant; and (3) *mutualistic symbionts*, usually called symbionts in the literature, which develop activities beneficial to plant growth.

TABLE 2.8
Examples of Some Interactions between Microorganisms and Plants that Are Either Detrimental (Negative) or Beneficial (Positive) to Plant Growth

Negative	Positive
Root pathogens	Nitrogen fixation (*Rhizobium*, *Frankia*), associated N fixation
Subclinical root pathogens	Mycorrhiza
Detrimental rhizobacteria	
Cyanide production	Biocontrol of detrimental microorganisms
Denitrification	Hormone/growth factor production
	Plant-growth-promoting rhizobacteria
	Phosphate solubilization
Nutrient unavailability	Nutrient availability

Source: Compiled from Bowen, G.D. and Rovira, A.D., The rhizosphere: The hidden half of the hidden half, in *Plant Roots: The Hidden Half*, Waisel, Y. et al. (eds.), Dekker, New York, 641–669, 1991.

The most beneficial contribution of soil microorganisms to plant development involves the supply of nutrients. Among these microorganisms, those concerned with N fixation and the enhancement of nutrients supplied by diffusion are especially relevant (Barea and Aguilar, 1983). A brief discussion of these two types of microorganism is given in this section.

2.2.2.4.1 Symbiotic Nitrogen Fixation

Nitrogen fertilizer is quite expensive due to the high price of natural gas used in its production. Under these circumstances, the ability of legumes in symbiosis with rhizobia to fix atmospheric nitrogen is important in crop production. Biological nitrogen fixation reduces the cost of production and helps reduce pollution. It is accepted that more than 60% of the N input to the natural plant community has a biological origin (Postgate and Hills, 1979). The N-fixing bacteria, in symbiotic association with plants, either converts N into bacterial proteins or makes it directly available to plants as NH_3.

Nitrogen fixation in legumes is termed obligatory because both the host plant and the organism are required for fixation to occur (Bezdicek, 1979). A classical example is the association between dicotyledonous plants of the family Leguminosae and members of the bacterial genus *Rhizobium*. Plants in this category include legumes, such as soybean, peas, alfalfa, and beans. Certain species of *Rhizobium* can produce nodules only on certain legumes. For example, bean is nodulated only by bacteria called *R. phaseoli*. Table 2.9 shows *Rhizobium*-legume associations.

The quantity of nitrogen fixed by a plant depends on the plant species, the soil environment, and the management practices. Burns and Hardy (1975) averaged a great many published estimates to arrive at an average figure of 140 kg N fixed per year per hectare of arable land under legumes. Shortly thereafter, that figure was considered by a group of scientists attending a conference on nitrogen-fixing microbes. They concluded that a more realistic figure would be half the Burns–Hardy value (Larue and Patterson, 1981). That is, on average 70 kg N $year^{-1}$ ha^{-1} is fixed by legumes. This is quite an impressive figure from a practical agricultural point of view. However, there is no concrete evidence that any legume crop satisfies all its N requirements by fixation, especially at higher yield levels. This suggests that inorganic N fertilizers have to be applied if higher productivity is the goal.

Further, over the last 20 years, many new species of N_2-fixing bacteria have been discovered in association with grasses, cereals, and other non-nodulating crops. Virtually all of these bacteria are microaerophilic, fixing N_2 only in the presence of low partial pressures of oxygen. Until a few years ago, much attention was focused on members of the genus *Azospirillum*, and it was assumed that N_2 fixation was restricted to the rhizosphere or the rhizoplane of the host plants. Through the use of N balance and ^{15}N techniques, it has been shown that in the case of lowland rice, several tropical pasture grasses, and especially sugar cane, the contributions of biological N_2 fixation (BNF) are of agronomic significance (Boddey and Dobereiner, 1995; Dobereiner et al., 1995).

TABLE 2.9
Legume Crops Nodulated by Rhizobium Bacteria

Crop	Rhizobium Species
Alfalfa	*Rhizobium meliloti*
Sweet clover	*Rhizobium meliloti*
Bean	*Rhizobium phaseoli*
Clover	*Rhizobium trifoli*
Cowpea	*Rhizobium japonicum*
Soybean	*Rhizobium japonicum*
Peanut	*Rhizobium japonicum*
Pea	*Rhizobium leguminosarum*

A more detailed study of N_2-fixing bacteria associated with sugarcane (*Acetobacter diazotrophicus* and *Herbaspirillum* spp.) has shown that they occur in high numbers, not only in roots of this crop but also in the stems, leaves, and trash, but are rarely found in the soil. Some of these endophytic diazotrophs have now also been found in forage grasses, cereals, sweet potato, and cassava, although evidence of significant BNF contributions is still lacking (Boddey and Dobereiner, 1995).

2.2.2.4.2 Mycorrhizae

Mycorrhizae have been shown to increase plant absorption of nutrients whose uptake is limited by diffusion through the soil matrix to the roots, such as P, Zn, Cu, and Fe (Tinker, 1982). Mycorrhizae accomplish this primarily by extension of the root geometry. In this symbiotic association, the fungus utilizes carbohydrates produced by the plant, while the plant benefits by an increased uptake of nutrients. The beneficial effect of mycorrhiza is of special importance for plants that have a coarse and a poorly branched root system, since the external hyphae can extend as much as 8 cm away from the roots (Mosse, 1981), absorbing nutrients from a much larger soil volume than the absorption zone surrounding a nonmycorrhizal root (Howeler et al., 1987).

Vesicular-arbuscular mycorrhizal (VAM) fungi are present in nearly all natural soils, and these fungi infect the great majority of plants, including the major food crops. Many tropical crops and pastures are grown on soils that are very P deficient, and particularly in those soils, an efficient mycorrhizal association is of great importance in increasing P uptake and crop yields (Howeler et al., 1987).

A great deal of work has been done on mycorrhizae, but much remains to be learned, especially about their practical application. One problem with mycorrhizae that has recently been recognized is that the symbiosis appears to form a large sink for host plant carbohydrates. Some ectomycorrhizae consume up to 50% of the C fixed by host photosynthesis (Lauchli, 1987). The ectomycorrhizae are those that primarily colonize forest trees. Estimates of the C drain for VAM, those that colonize root systems for many perennial and annual crop species, are lower, ranging from 6% to 20% of the C fixed by the host plant (Lauchli, 1987). Much research is needed to modify the fungus or the environment to reduce the fungal demand for host plant carbohydrates while maintaining the efficiency of fungal nutrient absorption and translocation to the plant.

2.2.2.5 Plant

Crop productivity results from the complex interaction of many characteristics of the plant with each other and with the environment. Plant factors that affect crop productivity include genetic variability, intolerance to stress, C_3 or C_4 metabolism, photosynthetic efficiency, plant architecture, harvest index, and plant density. How these factors affect crop yield and, consequently, production is discussed in this section.

2.2.2.5.1 Genetic Variability

Genetic variability in relation to yield is defined as the inheritable characteristics of a plant species or cultivar that make it differ in yield potential in favorable or unfavorable environments as compared to other species or cultivars within species. Plant breeders, pathologists, and entomologists have long exploited this variability by crossing and selecting germplasm resistant to a wide variety of diseases (Day, 1973; Buddenhagen, 1983; Urrea et al., 2005; Horsley et al., 2006) and insects (Beck, 1965). In comparison, relatively little emphasis has been placed on the selection of germplasm for nutritional stress (Duvik et al., 1981; Lafever, 1981; Clark, 1982; Epstein and Rains, 1987; Epstein and Bloom, 2005; Fageria, 2009) or drought (Unger et al., 1981; Bruckner and Frohberg, 1987; Fageria et al., 2006). Nevertheless, substantial differences have been found in the genotypic tolerance of nutrient deficiencies and toxicities (Fageria, 2009).

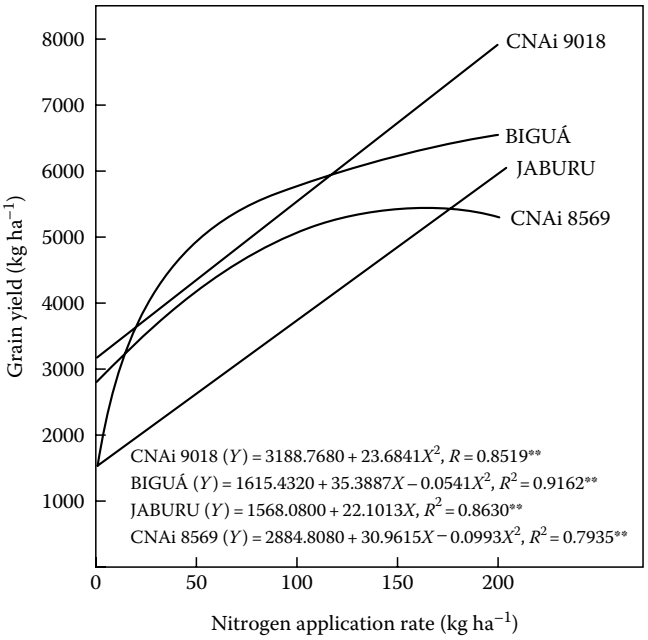

FIGURE 2.17 Response of four lowland rice genotypes to N fertilization.

Figure 2.17 shows the responses of four lowland rice genotypes to N fertilization. These genotypes differed in yield response to the applied N. Genotype CNAi9018 produced above average yields compared to all the other genotypes tested at the low N level, and responded well to the applied N. As a result, it can be classified as efficient and responsive. In contrast, Genotype CNAi 8569 produced well at low N rates but did not respond well at higher N rates. It can be called efficient but nonresponsive. The third type of response was found in the varieties Bigua and Jaburu that produced low yields at low N rates, but responded well to higher N rates. These have been designated as inefficient and responsive. From a practical point of view, the genotypes that fell into the efficient and responsive group would be the most desirable, because they can produce well at low soil N levels and also respond well to the applied N. Thus, this group could be utilized with low, as well as high input technology with reasonably good yields. The second most desirable group would be efficient and nonresponsive. Genotypes of this type can be planted under a low N level and still produce more than average yields. The inefficient and responsive genotypes could be used in breeding programs for their N-responsive characteristics.

Several reasons have been cited as to why some genotypes are more efficient in N utilization compared to others (Baligar et al., 2001; Thomason et al., 2002; Fageria and Baligar, 2005; Fageria et al., 2008). Moll et al. (1982) reported that N-use efficiency differences among corn hybrids were due to the differing utilization of N already accumulated in the plant prior to anthesis, especially at low N levels. Eghball and Maranville (1991) reported that N-use efficiency generally parallels water-use efficiency in corn. Hence, both N-use and water-use efficiency traits might be selected simultaneously where such parallels exist. Kanampiu et al. (1997) reported that wheat cultivars with higher grain harvest indexes had higher N-use efficiencies. Cox et al. (1985) reported that wheat cultivars that accumulate large amounts of N early in the growing season do not necessarily have high N-use efficiency. Plants must convert this accumulated N to grain N and must assimilate N after anthesis to produce high N-use efficiency. Forms of N uptake (NH_4^+ vs. NO_3^-) may also have effects on N-use efficiency (Thomason et al., 2002). Plants with preferential uptake of NH_4^+ during grain fill may provide increased N-use efficiency over plants without this preference (Tsai et al., 1992). Ammonium-N supplied to high-yielding corn

genotypes increased yield over plants supplied with NO_3^- during critical ear development (Pan et al., 1984). Salsac et al. (1987) reported that NH_4^+ assimilation processes require 5 ATP (adenosine triphosphate) mol^{-1} of NH_4^+, whereas, NO_3^- assimilation processes require 20 ATP mol^{-1} NO_3^-. This energy-saving mechanism may be responsible for the higher N-use efficiency in NH_4^+-N (Fageria and Baligar, 2005).

Crop genetic resources are principally the *product* of a complex interaction over time between the abiotic and biotic environments, and farmers' handling and the selection of the material. This interaction involves introgressions from wild and weedy relatives, hybridization with other cultivars, mutations, and natural and human selection pressure. The results of this evolutionary process are materials or "landraces" that are well adapted to the local abiotic and biotic environmental variations (Weltzien and Fischbeck, 1990). Landraces are often genetically heterogeneous populations; the genetic variation within landraces is supposed to be a consequence of the variation in environmental conditions under which the material evolved (Almekinders et al., 1995).

Because genetic variation has the potential to adapt to environmental variation, it also may be considered a *tool* in agricultural production. Genetic variation within and between crops often favors production stability in time and space through a suppression of pests, diseases, and weeds (Altieri and Liebman, 1986). Stability may be defined as the variability of a genotype across environments. The coefficient of variation v of yields in different environments then, is an appropriate stability measure (Lin et al., 1986; Hühn, 1987). Since v may be approximately $\acute{o} = (\Sigma_i c_i)^{½}$, c assesses the contribution of the ith component to the instability of the yield. In breeding programs, the c_i values can help identify key components responsible for yield instability. In order to stabilize the yield, it may then be a promising strategy to improve the stability of these key components of the yield.

Plant species or cultivars that produce better under unfavorable conditions do not necessarily produce better under favorable conditions and vice versa. Therefore, in selecting a species or cultivar under unfavorable conditions, the objective should be to stabilize productivity. Yield stability is a measure of variation between the potential and the actual yield of a genotype across changing environments (Blum, 1980). Yield stability can result from genetic heterogeneity, yield component compensation, stress tolerance, capacity to recover rapidly from stress, or a combination of these factors (Heinrich et al., 1983).

Under favorable conditions, the objective should be to increase productivity. Under these conditions, inputs are higher, and higher productivity is essential to compensate for the cost of production. Although ample variation exists for many characteristics, their ease of manipulation in a breeding program and the eventual incorporation into improved cultivars depend on the type of genetic control, the amount of genetic variation available, and its heritability (Cooper, 1973). Genetic correlations between desirable and undesirable characters may also be important limitations in breeding programs. Finally, success in this regard depends on the collaboration and joint efforts of soil scientists, plant pathologists, plant physiologists, agronomists, and breeders to achieve these objectives.

2.2.2.5.2 C_3 and C_4 Plants

Plant species have been classified into C_3 and C_4 groups according to their pathway of carbon dioxide fixation. Plants whose first carbon compound in photosynthesis consists of a three-carbon-atom chain are called C_3 plants, and plants whose first compound in photosynthesis consists of a four-carbon-atom chain are called C_4 plants. Plants in the C_4 group have high photosynthetic efficiency as compared with plants in the C_3 group. Characteristics that distinguish the two groups of higher plants are presented in Table 2.10. According to the characteristics presented in this table, it is clear that the C_4 plants represent an adaptation to habitats with high temperature, high irradiance, and limited water supply (Bjorkman, 1971; Black, 1971; Pearcy and Ehleringer, 1984). Important field crops in these groups are presented in Table 2.11. The readers are referred to the articles of Downton (1971, 1975) and Black (1971) for detailed discussions of C_3 and C_4 plants.

TABLE 2.10
Characteristics of C_3 and C_4 Plants

Characteristics	C_3	C_4
Photosynthetic efficiency	Low	High
Photorespiration	High	Low
Water utilization efficiency	Low	High
Optimum temperature for photosynthesis	10°C–25°C	30°C–45°C
Response to light intensity	Low	High
Response to CO_2 concentration	Low	High
Response to O_2 concentration	Low	High
Major pathway of photosynthetic CO_2 fixation	Reductive pentose phosphate cycle	C_4-dicarboxylic acid and reductive pentose phosphate cycle
Transpiration ratios	High	Low
Leaf chlorophyll *a* to *b* ratio	Low	High

TABLE 2.11
C_3 and C_4 Field Crops

C_3 Crop	C_4 Crop
Rice (*Oryza sativa* L.)	Sugarcane (*Saccharum officinarum* L.)
Wheat (*Triticum aestivum* L.)	Sorghum (*Sorghum vulgare* Pers.)
Oat (*Avena sativa* L.)	Corn (*Zea mays* L.)
Barley (*Hordeum vulgare* L.)	Pearl millet (*Pennisetum americanum* L.)
Peanut (*Arachis hypogaea* L.)	
Sugar beet (*Beta vulgaris* L.)	
Soybean (*Glycine max* L. Merr.)	
Cotton (*Gossypium hirsutum* L.)	
Common bean (*Phaseolus vulgaris* L.)	
Cowpea (*Vigna unguiculata* L. Walp.)	
Annual ryegrass (*Lolium multiflorum* Lam.)	
Potato (*Solanum tuberosum* L.)	

2.2.2.5.3 Photosynthetic Efficiency

Photosynthesis is the basis of all crop yields. It provides 90%–95% of plant dry weight. Thus, the net photosynthesis of the entire plant canopy integrated over a growing season should mainly determine total plant dry weight and thereby indirectly determine the economic yield (Kueneman et al., 1979; Fageria et al., 2006).

In the process of photosynthesis, light energy is converted into chemical potential energy. In photochemical reaction, carbohydrate is produced and O_2 and water are released according to the following equation:

$$6H_2O + 12H_2O \underset{\text{Energy}}{\overset{\text{Sunlight}}{\Rightarrow}} C_6H_{12}O_6 + 6O_2 + 6H_2O$$

Chloroplasts are important components of green plant cells insofar as they are the site where photosynthesis takes place. Chloroplasts contain chlorophyll, a substance that is capable of absorbing solar energy and, through a set of chemical reactions, converting this light energy into food materials.

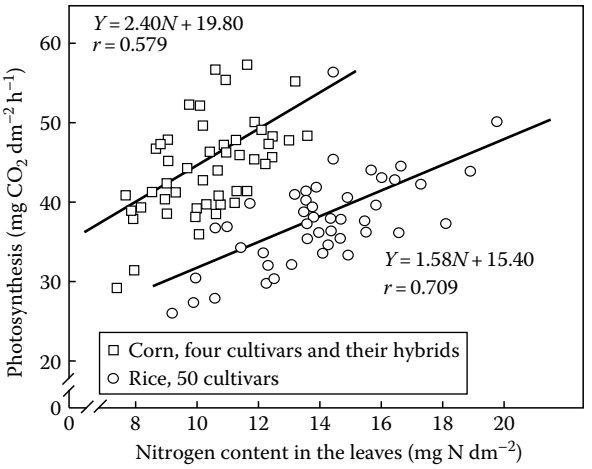

FIGURE 2.18 Relationship between nitrogen content in the leaves and photosynthesis rate in corn and rice plants. (From Akita, S., Economic aspects relation to increase commercial and biological production potential of rice, in *Rice in Latin America: Perspective to Increase Production and Production Potential*, Peneiro, B.S. and Guimares, E.P. (eds.), Document No. 60, EMBRAPA-CNPAF, Goiânia, Brazil, 57–76, 1995.)

The maximum possible efficiency of total solar energy conversion by crops is between 6% and 8% (Loomis and Williams, 1963; Monteith, 1978), but for many crops growing in a wide range of environments the ceiling biological yield is achieved with a radiant energy conversion of approximately 1%–2% (Holliday, 1966; Gibbon et al., 1970). Energy conversion efficiency in crop plants can be calculated from the formula:

$$\text{Efficiency} = \frac{\text{Energy content of dry matter}}{\text{Total solar energy available}}$$

The low energy conversion efficiency is related to nutrient and water deficiency, inadequate temperature and pest control, and poor management practices.

The photosynthetic rate of leaf tissue varies markedly among plant species. Corn, sorghum, the millets, sugarcane, many tropical and warm-season temperate forage grasses, and certain other species have maximum photosynthetic rates of 50–60 mg CO_2 dm^{-2} h^{-1}, whereas 20–30 mg dm^{-2} h^{-1} is the maximum rate in small grains, temperate grasses, and many other plants (Hesketh and Moss, 1963; Murata and Iyama, 1963; Menz et al., 1969).

The photosynthetic rate of plant species is also affected by N concentration in the leaves (Figure 2.18). Considerable genetic variability for leaf N concentration and photosynthetic capacity exists, and it seems possible that photosynthetic rates can be increased through selection and breeding (Loomis and Williams, 1963). Leaves of most C_3 crop plants appear to be reasonably efficient at low light intensities, and the need is to extend these efficiencies to higher light intensities.

2.2.2.5.4 Plant Architecture

Plant architecture influences photosynthesis, growth, lodging, and yield. Crop physiologists have proposed plant ideotypes or model cultivars, with plant architectures designed to maximize crop yields by maximizing photosynthesis and by the conversion of dry weight into grain (Donald, 1968;

Donald and Hamblin, 1976). Donald and Hamblin (1976) proposed that the principal characteristics of the ideotype for all annual seed crops are as follows:

1. Strictly annual habit—to favor translocation of carbohydrates and nutrients from the vegetative parts of the plant to the seed as the seed matures and the plant senesces
2. Erect growth form—to distribute solar radiation over the maximum amount of leaf area
3. Dwarf stature—to minimize lodging and to reduce the amount of structural carbohydrate needed to produce the stems
4. Strong stems—to reduce lodging
5. Unbranched or nontillered habit—to reduce the carbohydrates and the nutrients used to produce excess (sterile) tillers
6. Reduced foliage (smaller, shorter, narrower, or fewer leaves)—to reduce the carbohydrates and the nutrients needed to produce leaves in excess of those needed to intercept all incident radiation
7. Erect leaf disposition—to distribute solar radiation over the maximum amount of leaf area
8. Determinate habit—to favor translocation of carbohydrates and nutrients from the vegetative parts of the plant to the seed as the seed matures and the plant senesces
9. High harvest index—to maximize the conversion of the biomass to seed production
10. Nonphotoperiodic for most but not all situations—to increase adaptability to different latitudes and planting dates
11. Early flowering for most but not all situations—to maximize the time available for grain filling
12. High population density—to increase light interception, especially early in the season
13. Narrow rows or square planted—to increase light interception
14. Response to high nutrient levels—to increase yield potential under favorable conditions
15. Wide climatic adaptation—to increase adaptability to different latitudes and planting dates

2.2.2.5.5 Nitrogen Harvest Index and Grain Harvest Index

Nitrogen harvest index (NHI) is defined as the percentage of the total above-ground plant N that is in the grain at harvest. The NHI is positively related to grain yield in crop plants (Figure 2.19). The amount of N remobilized from vegetative tissues to the grain during grain filling is an important determinant of NHI. The NHI also varies among crop species and among genotypes and appears to be under genetic control (Moll et al., 1982; Dhugga and Waines, 1989; Fageria, 2009). A mean NHI value of 82% was reported for the faba bean (Lopez-Bellido et al., 2003). This index is very useful in measuring N partitioning in crop plants, which provides an indication of how efficiently the plant utilized the acquired N for grain production (Fageria and Baligar, 2005). The genetic variability for NHI exists within crop genotypes, and high NHI is associated with the efficient utilization of N (Fageria and Baligar, 2005). Dhugga and Waines (1989) reported that wheat genotypes accumulate little or no N after anthesis, and had low grain yields and low NHIs. Thus, NHI may be useful in selecting crop genotypes for a higher grain yield (Fageria and Baligar, 2005).

Soil and crop management practices also influence NHI. In winter wheat, NHI values ranged from 51% to 54% for moldboard plowed conditions compared with 58%–64% for no-till conditions (Rao and Dao, 1996). These results suggest that subsurface N fertilizer placement in plowed plots was less effectively absorbed by the crop and translocated to the seed than the N fertilizer banded below the seed in no-till plots (Rao and Dao, 1996).

Crop production can be measured as the total biomass or economically useful parts of the plant. The total yield of plant material is known as biological yield, and the ratio of the yield of grain to the biological yield is the grain harvest index (Donald and Hamblin, 1976). The efficiency of grain production in crop plants is frequently expressed as the grain harvest index. The grain harvest index, by definition, is a factor less than 1, but some workers prefer to express it as a percentage. Grain yield in crop plants is positively associated to the grain harvest index (Figure 2.19). Increases in the grain

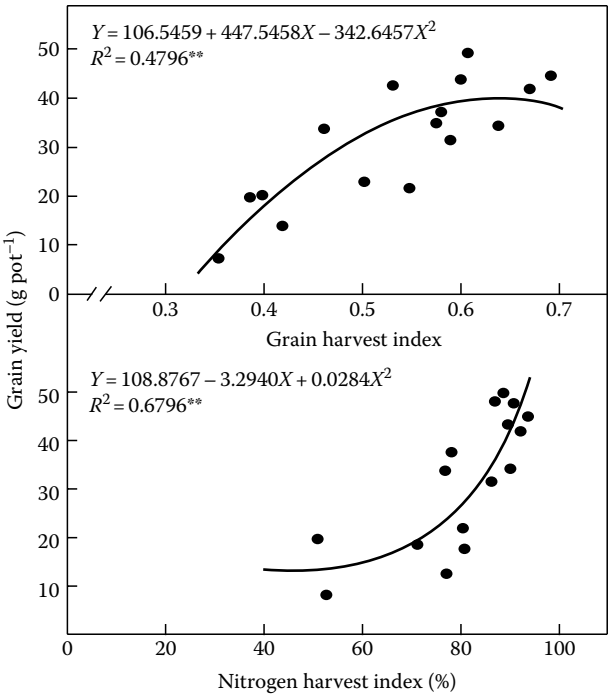

FIGURE 2.19 Relationship between nitrogen harvest index, grain harvest index, and grain yield of dry bean grown on Brazilian lowland soil. (From Fageria, N.K. and Santos, A.B., *J. Plant Nutr.*, 31, 983, 2008.)

TABLE 2.12
Grain Harvest Index (%) of Five Cereal Crops

Crop	Minimum	Maximum	Average
Millet	16	40	26
Sorghum	25	56	27
Corn	25	56	42
Rice	34	55	44
Wheat	35	49	41

Source: Adapted from van Duivenbooden, N. et al., *Fert. Res.*, 44, 37, 1996.

harvest index have contributed significantly to the increasing yields of rice and wheat, and a value of more than 50% has been achieved in these cereals. But there is clearly a limit to how much further the harvest index can be improved. It seems unlikely that it will be able to rise much above 60% in cereals, although it may increase further in roots and tuber crops (Evans, 1980). Further increases in yield potential will then depend on improvements in the rates of photosynthesis and growth. Typical grain harvest indices of important crop species are given in Table 2.12.

2.2.2.5.6 Plant Density

Plant density is an important agronomic factor affecting crop yields. Biological yield increases with density to a maximum value determined by some factor of the environment, and at higher densities tends to remain constant, provided there are no interfering factors, such as lodging. Grain yield increases to a maximum value but declines as the density is further increased. Figure 2.20 shows

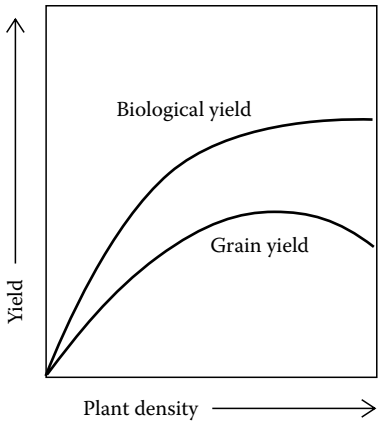

FIGURE 2.20 Relationship between plant density and yield.

hypothetical relationships between plant density and biological and grain yield. Optimum plant density should be determined for each crop under each agroecosystem to obtain maximum yield. This parameter has special importance in crop production because it normally costs very little for farmers to adopt appropriate plant densities.

Adequate plant density not only improved the grain yield of crops but also improved the nutrient-use efficiency. Shapiro and Wortmann (2006) reported that the efficient use of N by corn is financially and environmentally important, and may be improved with a higher plant density and reduced row spacing. The effect of increasing plant density of corn by decreasing row spacing from a mean of 1.07 m to 0.90 m was estimated to result in an overall mean yield increase of 175 kg ha^{-1} (Cardwell, 1982), while most farmers in the United States have reduced corn row spacing to 0.76 m or less (Shapiro and Wortmann, 2006). Nielsen (1988) and Widdicombe and Thelen (2002) reported that corn yields may be further increased by reducing row spacing from 0.76 to 0.38 m, but there may be little advantage to further reduction (Porter et al., 1997). Plant nutrient demand also increases as plant density increases (Penning de Vries et al., 1993).

2.2.2.5.7 Irrigation

The world population is projected to be 9 billion by 2050 (Horrigan et al., 2002). Food supply should be increased to properly feed this increase in population. Increase in irrigated areas and improvement in irrigation efficiency are key points in improving food supply worldwide in the twenty-first century. This is especially applicable where fresh water resources are available. Irrigation can be an effective way to stabilize and to intensify agricultural production. Currently, only 20% of the world's farmland is irrigated, but that farmland produces 40% of the world's food supply (Howell, 2001). The highest yields obtained from irrigation are more than double the highest yields for rainfed agriculture (Bhattarai et al., 2005). For example, in Brazil, the average yield of irrigated rice is about 5 Mg ha^{-1} compared to upland rice (rainfed) that is about 2 Mg ha^{-1}. In spite of a higher yield of crops in the irrigated areas, irrigation water efficiency along with efficiency of other inputs needs to be improved. Presently, most of the world's irrigation is by furrow, where the irrigation efficiency (irrigation efficiency is expressed as the ratio of crop water used to applied irrigation water) stands at only 50%–60% and is associated with large losses of water that at times lead to significant waterlogging and salinization (Jensen et al., 1990). One option for increasing irrigation efficiency is to adopt the drip irrigation system. The irrigation efficiency in drip irrigation is close to 100% and environmental degradation can be significantly reduced (Camp, 1998). Bhattarai et al. (2005) reported that with the adoption of drip irrigation technology, the area under irrigation could be almost doubled, or the current production level could be achieved, with as little as half of today's global irrigation water allocation.

2.2.2.5.8 Socioeconomic Factors

Besides climatic, soil, and plant factors, socioeconomic factors play an important role in crop production. Though crop production and biodiversity are threatened by excessive soil erosion, deforestation, salinization of soils, and other degradation processes. Famines in some parts of the world appear to be more closely related to socioeconomic factors than to any other cause. The quantity and the quality of global soil resources seem capable of supporting present civilization at least well into the twenty-first century, but local areas of hunger will continue because of local and regional conflicts and political and economic conditions (McCracken, 1987).

Farmers need efficient markets in which to buy inputs and sell their excess products at a reasonable price. This typically requires political stability, adequate transportation systems, and public and/or private institutions capable of meeting farmers' needs for information, credit, inputs, and sale of their crops. In many parts of the world government-supported extension services have long been a source of valuable technical information for farmers and their families. This public service has declined in many developed and developing countries where access to technical information has improved, and, in some cases, the private sector has assumed a greater role in providing technical information about crop production. However, extension remains an important public service for educating farmers and their families about ways to improve agricultural technologies, conserve natural resources and strengthen farm families and communities.

2.3 SUMMARY

Crop yield is the product of interactions involving climate, soil, plants, and people. A quantitative evaluation of these factors and their interactions should become increasingly important in evaluating systems that optimize yield. The best evidence that these factors are not limiting crop growth is provided when high crop yields are produced. Most of the crop production factors can be modified in favor of higher yields by modifying the environment or the physiological characteristics of the crop and by developing cultural practices and cultivars to exploit a specific agricultural environment.

The dramatic increase in yields of most important food crops since the middle of the twentieth century is beginning to level off. The favorable mix of genetics and technology that has characterized this area must be improved on to achieve even higher yields in the future. It is obvious that much research and development activity must be performed to remove the biological, physical, and socioeconomic constraints to increased crop production. Yields obtained under experimental conditions are much higher that those under farm conditions. It is important to accurately identify the constraints limiting the farmers' yields.

The potential for yield increases is greatest in South America, Africa, and Asia, where both land area and yields per unit area can be increased. Some important strategies for improving yields in these regions are (1) evaluating environmental constraints, such as climate and soils and developing economically viable methods for improving these constraints; (2) increasing intensities of cropping to permit more complete utilization of soil and water resources; (3) developing cultivars resistant to diseases, insects, and mineral stress; and (4) whenever possible, increasing irrigation facilities that will permit higher cropping intensity and the use of new technology.

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3 Nutrient Flux in Soil–Plant System

3.1 INTRODUCTION

Nutrient flux in the soil–plant system is controlled by complex interactions among plant roots, soil microorganisms, chemical reactions, and pathways for loss. The concentration dependence of most of the processes that take place in the soil implies that when the immediate supply exceeds the ability of the plant to take up a nutrient, various processes will act to reduce its concentration (Shaviv and Mikkelsen, 1993). Such processes include transformations induced by microbes such as nitrification, denitrification, and immobilization. Further included are chemical processes such as exchange, fixation, precipitation, and hydrolysis as well as physical ones such as leaching, runoff, and volatilization. The extent by which nutrients are removed from solution by the processes competing with plant uptake can thus affect both nutrient use efficiency and the environment (Shaviv and Mikkelsen, 1993).

Nutrient uptake by plants depends on ion concentrations at the root surfaces, root absorption capacity, and plant demand. It is a dynamic series of processes in which nutrients must be continuously replenished in the soil solution from the soil solid phase and transported to roots as uptake proceeds. After uptake by roots, nutrients are translocated to the various plant organs for utilization in different metabolic processes. In this way, nutrient uptake by plants involves several interconnected processes such as nutrient release from the soil solid phase to solution, transport to roots for absorption, and plant translocation and utilization. The consequence is that nutrient uptake by plants is simultaneously influenced by soil, climatic, and plant factors. Nutrient transport to roots, absorption by roots, and translocation in the shoot, all occur simultaneously. This means that a rate change of one process will ultimately influence all other processes involved in uptake. In other words, if one process slows down, it may become the limiting factor in the uptake process. Only inorganic nutrients can be absorbed by plants. If nutrients are present in organic forms, they have to undergo mineralization before uptake by plants can occur.

3.2 NUTRIENT SUPPLY TO PLANT ROOTS

Transport of the nutrients to the vicinity of roots is the first step in the process of nutrient absorption by plants. Nutrient supply to the roots is governed by nutrient concentrations in the soil solution, nature of the nutrients, soil moisture status, and plant's absorption capacity. The concentration of a nutrient in the solution immediately adjacent to a root appears to be the best measure of its availability for absorption, though many factors within the plant and the concentrations of other ions in the solution phase may influence the actual rate at which it is absorbed (Russell, 1977).

Research in recent decades has shown that plant and soil properties interact in the transfer of nutrients from the soil into the plants (Jungk and Claassen, 1989). The major processes and factors that contribute and interact in the transfer of nutrients from the soil into roots are summarized in Table 3.1. In the soil system, nutrients move to plant roots by mass flow, diffusion, and root interception. The importance of these processes in supplying nutrients to plant roots is discussed in this section.

TABLE 3.1
Processes and Factors Involved in Nutrient Transfer from Soil to Plant

Process	Factors
Root development	Root length
	Root distribution
	Root morphology, diameter, and hairs
Nutrient uptake	Concentration at root surface
	Kinetics of uptake
Transport from soil to root	Transpiration
Mass flow, diffusion	Concentration of soil solution
	Concentration of gradient
Mobilization by roots	Depletion of soil solution
Desorption, dissolution, hydrolysis of organic compounds	Root exudates (H^+, HCO_3^-, reducing agents, chelates, organic anions)
	Chemical soil composition
	pH of soil solution
	Enzymes (e.g., phosphatases)
Mobilization by associated organisms	Mycorrhizal infection
	Bacteria

Source: Adapted from Jungk, A.O., *Plant Roots: The Hidden Half*, Marcel Dekker, New York, 1991.

3.2.1 Mass Flow

Mass flow is the passive transport of nutrients to the root as soil water is absorbed by plants. The amounts of nutrients reaching roots by this process depend on the concentrations of nutrients in the soil solution and the rate of water transport to and into the roots. The amounts of nutrients supplied by mass flow are affected by soil properties, climatic conditions, solubility of the nutrient, and plant species. The level of a particular nutrient in the soil solution near the root may increase, stay the same, or decrease depending on the balance between the rate of supply to the root by mass flow and the rate of absorption into the root (Barber, 1995).

The contribution of mass flow in the process of nutrient supply to the roots can be calculated from the product of the soil solution concentration and the volume of water transpired by the plant. This, however, does not take into account mass flow of the soil solution, which is not due to the water uptake by the root, such as gravity-induced movement of water down the soil profile. Mass flow rate can be calculated with the help of the following equation:

$$\mathrm{MF} = C \times \mathrm{WU}$$

where

MF is the contribution to ion uptake by mass flow
C is the solution concentration of any given ion
WU is the total water uptake, which is the water content in the plant plus the water transpired

Transpiration is not a constant process. It varies with plant species, climate, soil conditions, location of water source in soil, age of plants, and time. At night, mass flow is greatly restricted, which causes diurnal fluctuations at the root surface. Furthermore, nutrient concentrations in plants vary with development stages. Young plants usually have higher concentrations of nutrients; therefore, mass flow may then contribute a smaller fraction of the demand (Jungk, 1991). Table 3.2 shows the estimates of nutrients supplied to corn roots by three processes. In this example, mass flow can meet the crop's nutrient requirements for all nutrients except N, P, K, Fe, and Mn.

TABLE 3.2
Estimated Amounts of Nutrients Supplied by Mass Flow, Diffusion, and Root Interception to Corn Roots in a Fertile Alfisol

	Approximate Amount (% of Total Uptake)[a]		
Nutrient	**Mass Flow**	**Diffusion**	**Root Interception**
Nitrogen	79	20	1
Phosphorus	5	93	2
Potassium	18	80	2
Calcium	375	0	150
Magnesium	222	0	33
Sulfur	295	0	5
Iron	66	21	13
Zinc	230	0	43
Manganese	22	35	43
Copper	219	0	6
Boron	1000	29	29

[a] Calculated from the data of Barber (1966, 1995).

3.2.2 Diffusion

Diffusion can be defined as the movement of molecules from a region of high concentration to a region of low concentration. When the supply of the nutrients to the root vicinity is not sufficient to satisfy the plant demand by mass flow and root interception, a concentration gradient develops and nutrients move by diffusion. Diffusion is described by Fick's first law (Mengel, 1985; Barber, 1995):

$$F = -D\left(\frac{\mathrm{d}c}{\mathrm{d}x}\right)$$

where
- F is the flux
- $\mathrm{d}c/\mathrm{d}x$ the concentration gradient
- D is the diffusion coefficient that generally describes diffusivity in a homogeneous medium

Since the soil is not homogeneous, the concept of a diffusive flux in the soil medium presents difficulties. Nye (1979) proposed the following formula to calculate the diffusion coefficient for soil medium:

$$D = D_{\mathrm{e}}\theta f_{\mathrm{e}}\left(\frac{\mathrm{d}C_{\mathrm{e}}}{\mathrm{d}C}\right) + D_{\mathrm{E}}$$

where
- D is the diffusion coefficient in the whole soil medium
- D_{e} is the diffusion coefficient in free water
- θ is the fraction of the soil volume filled with solution
- f_{e} is the impedance factor
- C_{e} is the ion concentration in the soil solution
- C represents concentrations of labile forms in soil
- D_{E} is surface diffusion

TABLE 3.3
Diffusion Coefficients for Some Ions in Soil Solution

Ion	Diffusion ($cm^2\ s^{-1}$)	Reference
NO_3^-	1×10^{-6}	Nye (1969)
NO_3^-	10^{-6}–10^{-7}	Barber (1974)
NH_4^+	1.4×10^{-6}	Husted and Low (1954)
$H_2PO_4^-$	10^{-8}–10^{-11}	Barber (1974)
$H_2PO_4^-$	2.4×10^{-11}	Vasey and Barber (1963)
K^+	1.4×10^{-6}	Husted and Low (1954)
K^+	10^{-7}–10^{-8}	Barber (1974)
K^+	2.1–9.5×10^{-7}	Baligar (1984)
Ca^{2+}	0.9–4.0×10^{-7}	Baligar (1984)
Ca^{2+}	3×10^{-7}	Spiegler and Coryell (1953)
Mg^{2+}	0.6–11.5×10^{-7}	Baligar (1984)
Cl^-	1.2×10^{-6}	Dutt and Low (1962)
MoO_4^{2-}	0.5–8.4×10^{-7}	Lavy and Barber (1964)

In the process of diffusion, soil and plant factors are involved. The following equation illustrates the factors that are important in determining the rate at which a soluble nutrient diffuses to the root surface (Corey, 1973):

$$\frac{dq}{dt} = DAP\frac{C_1 - C_2}{L}$$

where

dq/dt represents the rate of diffusion to the root surface
D is the diffusion coefficient of the nutrient in water
A is the cross-sectional area considered, which can be assumed to represent the total absorbing surface of a plant root
P is the fraction of the soil volume occupied by water (it also includes a tortuosity factor)
C_1 is the concentration of the soluble nutrient at a distance L from the root surface
C_2 is the concentration of the soluble nutrient at the root surface
L is the distance from the root surface to where C_1 is measured

The distance for diffusive nutrient movement through the soil to the root is usually in the range of 0.1–15 mm (Barber, 1995). Hence, only soil nutrients within this soil zone contribute to diffusive nutrient supply to roots. Diffusion coefficients for some ions in soil solution are given in Table 3.3. It can be observed from Table 3.2 that phosphorus has the slowest diffusion rate. When an ion in the bulk soil solution is dilute and its diffusion is slow, its concentration at the root surface can be reduced very quickly (in the space of a few hours) to almost zero if plant demand is high. Table 3.2 shows that plant requirements for P and K are mostly met by the process of diffusion.

3.2.3 Root Interception

As roots grow in the soil, they push the soil aside and root surfaces come in direct contact with soil particles and plant nutrients. Nutrient interception by roots depends on the soil volume occupied by roots, root morphology, and the concentration of nutrients in the root-occupied soil volume. The amount of roots present per unit volume of soil can be measured in terms of root surface area, root length, or root volume. The root surface available for ion absorption is a function of surface

TABLE 3.4
Soil Volume Occupied by Roots of Different Crops at 0–15 cm Soil Depth

	Soil Volume Occupied (%)	Reference
Soybean (*Glycine max* L. Merr.)	0.91	Dittmer (1940)
Oats (*Avena sativa* L.)	0.55	Dittmer (1940)
Rye (*Secale cereale* L.)	0.85	Dittmer (1940)
Corn (*Zea mays* L.)	0.19–1.06	Barber (1971)
Wheat (*Triticum aestivum* L.)	0.64	Barber (1974)
Alfalfa (*Medicago sativa* L.)	1.1	Barber (1974)

area. Root density varies with soil properties, species, and management practices. Table 3.4 presents root density data obtained by different researchers for some important field crops. On the average, the soil volume occupied by roots of important food crops is around 0.7%–0.9%. Table 3.2 shows the quantity of nutrients intercepted by roots of corn in a fertile silt loam soil. The only nutrient which might be supplied completely by interception is Ca, although the process may provide a significant part of the requirement for Mg, Zn, and Mn.

3.3 ION ABSORPTION BY PLANTS

Nutrient absorption by plants is usually referred to as ion uptake or ion absorption because it is the ionic form in which nutrients are adsorbed (Hiatt and Leggett, 1974). Ion uptake by intact plants is certainly a catenary process. After reaching plant roots, ions have to enter into root cells, be transported from cell to cell toward the xylem, be excreted into the xylem vessels, and finally be transported to the growing organs in the plant. In such a chain process, the speed of the slowest link will finally govern the reaction velocity of the whole process (Becking, 1956). A great deal of work has been done on ion uptake in plants, but the process still is not fully understood. The overall process of nutrient uptake in the soil–plant system is summarized in Figure 3.1. In ion absorption, roots constitute the dominant organ of plants; therefore, a brief discussion of root morphology is important and is given in this section.

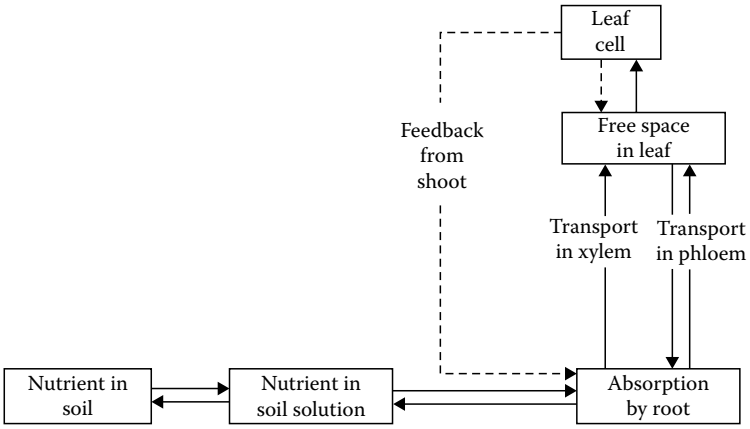

FIGURE 3.1 Process of nutrient uptake in soil–plant system. (Modified after Pitman, M.G., *Aust. J. Biol. Sci*., 25, 905, 1972.)

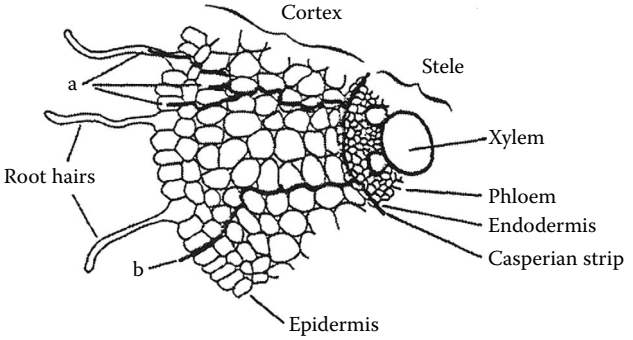

FIGURE 3.2 Transverse section of corn root showing the symplastic (a) and apoplastic (b) pathways of ion transport across the root. (Reproduced from Marschner, H., *Mineral Nutrition of Higher Plants*, Academic Press, New York, 1995. With permission.)

3.3.1 Root Morphology

The roots of most crop plants are similar in structure, although they may vary in size. A cross section of a root is shown in Figure 3.2. Root structures are composed of root hairs, epidermis, cortex, endodermis, and stele. Stele is composed of xylem and phloem. Ions absorbed by root hairs move through the epidermis, cortex, endodermis, and stele and finally to the xylem. Ions are translocated through the stele to the shoot, and the phloem moves photosynthate from shoots to roots. There are two parallel pathways of solute movement across the cortex to reach the stele: one passing through the extracellular space, or apoplast (cell wall and intercellular spaces), and another passing from cell to cell in the symplast through the plasmodesmata, which bypasses the vacuoles (Marschner, 1995).

3.3.2 Plant Cell and Membranes

Active nutrient uptake takes place across the plant cells, which are surrounded by membranes. Therefore, it is important to give a brief account of cell structure and membranes to facilitate understanding of nutrient uptake mechanisms. Figure 3.3 shows a simplified diagram of a mesophyll

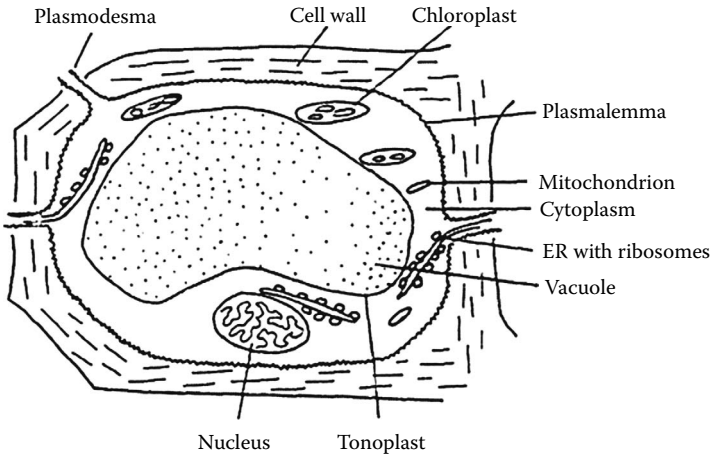

FIGURE 3.3 Simplified scheme of a mesophyll cell. (From Mengel, K. and Kirkby, E.A., *Principles of Plant Nutrition*, International Potash Institute, Bern, Switzerland, 1982.)

cell and its components. It has a vacuole, nucleus, chloroplasts, ribosomes, and mitochondria, all enclosed by a cell wall. The plasmalemma separates the cytoplasm and cell wall, while the tonoplast membrane separates the cytoplasm and vacuole. The plasmalemma membrane forms the boundary between the cell and the outer medium, and it is this membrane, and not the cell wall, which presents the effective barrier against uptake of all ions and molecules dissolved in the aqueous outer medium (Mengel et al., 2001).

Each of the plant cell organs has specific functions to facilitate plant growth and development. The vacuole plays an important role in the water economy of the cell, as well as providing a site for the segregation of water and the end products of metabolism. Chloroplasts are the organs in which light energy conversion and CO_2 assimilation take place. In the mitochondria, enzymes are present that control the various steps of the tricarboxylic acid cycle, respiration, and fatty acid metabolism. The ribosomes are super-molecular assemblies of ribosomal nucleic acid and proteins, which enable the synthesis of polypeptides from free amino acids. Plasmodesmata connect the cell to other cells (Mengel and Kirkby, 1982).

As far as membrane structure is concerned, biological membranes consist of protein and lipid molecules in approximately equal proportions and are about 7–10 nm thick (Mengel and Kirkby, 1982). Danielli and Davson (1935) proposed a unit-membrane model which presented biological membranes as a unit consisting of two lipid molecular layers in which the hydrophobic tails of the fatty acids are oriented inward (Marschner, 1995). Both outer boundaries of the lipid layer are coated with a protein layer (Figure 3.4a). It has been argued that this type of structure could well serve as a barrier to ion movement because the protein layer would enhance rigidity and the lipidic fraction would prevent penetration of the membrane by hydrophilic particles, including hydrated inorganic ions (Mengel and Kirkby, 1982).

Singer (1972), based on electron microscopic studies, proposed a membrane model consisting mainly of an amphiphilic lipid bilayer and amphiphilic proteins (Figure 3.4b). The term "amphiphilic" indicates the presence of both hydrophilic (OH groups, NH_2 groups, phosphorus groups, carboxylic groups) and hydrophobic (hydrocarbon chains) regions in the membrane. Lipids and proteins may thus be bound by electrostatic bonds, hydrogen bonds, and hydrophobic bonds (Mengel and Kirkby, 1982). In the Singer model, there is no coating protein on the outer sides of the membrane such as that which exists in Danielli–Davson model, and globular proteins are embedded in the lipid bilayer. Some of these proteins may even extend through the membrane, forming protein channels from one side of the membrane to the other. These channels can be considered the hydrophilic pores through which polar solutes such as ions are transported (Walker, 1976). Biological membranes are not completely impermeable. They may allow the diffusion of hydrophilic ions and molecules, the degree of permeability depending on the components which make up the membranes. In addition, enzymes present in biological membranes may directly or indirectly be involved in the transport of ions and molecules across the membrane (Mengel and Kirkby, 1982).

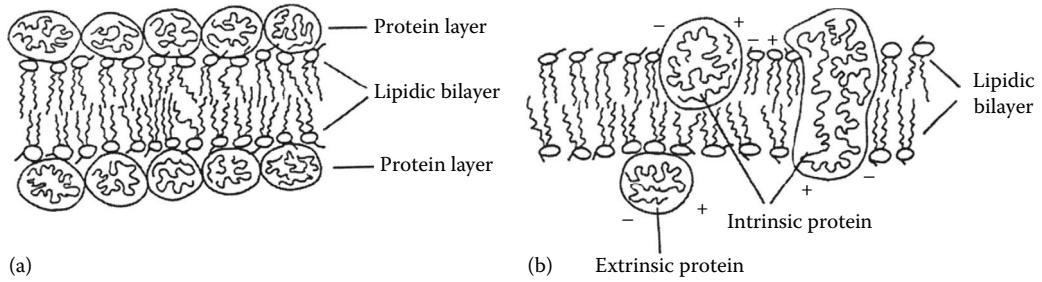

FIGURE 3.4 Biological membrane models: (a) Danielli–Davson and (b) Singer. (From Mengel, K. and Kirkby, E.A., *Principles of Plant Nutrition*, International Potash Institute, Bern, Switzerland, 1982.)

3.3.3 Active and Passive Ion Transport

Ion movements in plant cells are active and passive. In the passive process, ions move from a higher to a lower concentration or down a chemical gradient of potential energy. In the case of active uptake, ions move against a concentration gradient and ion movement depends on an electrochemical potential gradient. In the active process, cations are attracted to a negative electropotential, whereas anions are attracted to a positive electropotential. Electrochemical potentials are established across membranes by unequal charge distributions. The difference between the membrane potential and the actual potential created by the nonequilibrium distribution is a measure of the quantity of energy required. A modified Nernst equation that can be used to calculate electrical charge is as follows (Ting, 1982):

$$\Psi = \frac{RT}{ZF} ln \frac{a_i}{a_o}$$

where

- Ψ is the electrochemical potential between the root cells and the external solution in millivolts (mV)
- R is the gas constant (8.3 J mol^{-1} K^{-1})
- T is the absolute temperature (K)
- Z is the net charge on the ion (dimensionless)
- F is the Faraday constant (96,400 J mol^{-1})
- a_i is the activity of the ion inside the tissue
- a_o is the activity of the ion outside the tissue

For quick calculation, it is convenient to remember that $RT/F = 26$ mV.

Measurement of the electrochemical potential in the cell and outer medium and of the ionic concentrations in the cell and outer medium can give an indication whether the ions move actively or passively. Values from these measurements can be put into the Nernst equation to calculate electrical potential. For cations, a negative value indicates passive uptake and a positive value indicates active uptake. For anions, negative values are indicative of active transport and positive values are indicative of passive transport (Mengel and Kirkby, 1982). These measurements are only valid when equilibrium conditions are maintained in the system, which is difficult under practical conditions. The electrical potential difference across the plasma membrane is normally in the range of −60 to −200 mV (cytoplasmic negative), and the electrical potential difference across the tonoplast is relatively small, only 0 to −20 mV with the cytoplasm being negative relative to the vacuole (Hodges, 1973). This suggests that cations can move passively from the soil solution to the cytoplasm while the plant must expend energy to absorb anions.

3.3.4 Ion Uptake Mechanisms

The concentration of ions in the cytoplasm is often much higher than that in the soil solution, in extreme cases, 10,000-fold higher. Therefore, the roots must be able to take up ions against a considerable concentration gradient. Uptake against a concentration gradient or, strictly speaking, against an electrochemical gradient requires metabolic energy, and the process is commonly termed active uptake. At present, there are two principal theories of ion transport across the membrane: the carrier theory and the ion pump theory (Mengel and Kirkby, 1982).

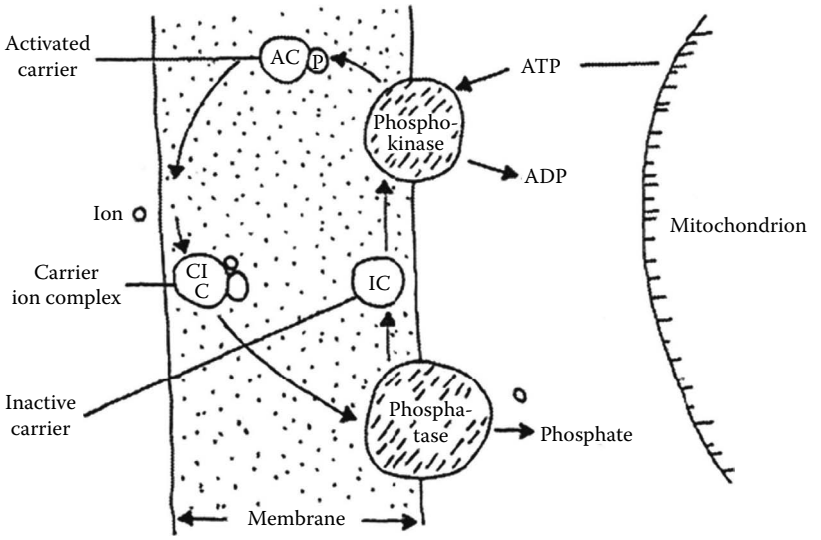

FIGURE 3.5 Carrier ion transport mechanism. (From Mengel, K. and Kirkby, E.A., *Principles of Plant Nutrition*, International Potash Institute, Bern, Switzerland, 1982.)

3.3.4.1 Carrier Theory

The term "carrier" is commonly used to refer to an agent responsible for transporting ions from one side of the membrane to the other. Carriers have properties similar to those of enzymes, but, unlike enzymes, carriers have not been isolated and characterized. Isolation of a carrier will not necessarily entail its removal from the membrane, but there is no way of measuring its activity. Figure 3.5 shows a hypothetical scheme of the carrier ion transport across a membrane. In this transport process, a carrier meets the particular ions for which it has affinity, forms a carrier ion complex, and moves across the membrane. The enzyme phosphatase, which is located at the inner membrane boundary, splits off the phosphate group from the carrier complex, and the ion is released. In this process of transport, energy is required and involvement of ATP (adenosine triphosphate) is reported (Marschner, 1995). The ATP is generated from ADP plus inorganic phosphate (P_i) via respiration (oxidative phosphorylation).

The whole uptake may be described as follows (Mengel and Kirkby, 1982):

$$\text{Carrier} + \text{ATP} \xrightarrow{\text{Kinase}} \text{carrier } \textcircled{P} + \text{ADP}$$

$$\text{Carrier } \textcircled{P} + \text{ion} \longrightarrow \text{carrier } \textcircled{P} - \text{ion}$$

$$\text{Carrier } \textcircled{P} - \text{ion} \xrightarrow{\text{Phosphatase}} \text{carrier} + P_i + \text{ion}$$

$$\text{Net}: \ \text{ion} + \text{ATP} \xrightarrow{\text{Transport}} \text{ion} + \text{ADP} + P_i$$

3.3.4.2 ATPase Theory of Ion Transport

Hodges (1973) proposed the ATPase theory of ion transport in plants (Figure 3.6). ATPase is a group of enzymes that have the capacity to dissociate ATP into ADP and inorganic phosphate. Energy liberated by this process can be utilized in ion transport across the membrane. In plants,

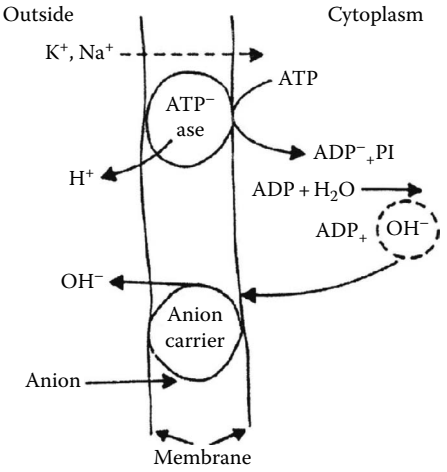

FIGURE 3.6 ATPase model of ion transport. (From Hodges, T.K., *Adv. Agron.*, 25, 163, 1973; Mengel, K. and Kirkby, E.A., *Principles of Plant Nutrition*, International Potash Institute, Bern, Switzerland, 1982.)

the phenomenon is known as activity of ATP, which is associated with the plasmalemma and is activated by cations (Hodges et al., 1972). A detailed description of this process of ion transport is given by Hodges (1973), Mengel and Kirkby (1982), and Clarkson (1984).

3.3.5 Ion Uptake Kinetics

Epstein and Hagen (1952) formulated the enzyme kinetic hypothesis of ion transport and carrier function. A brief description of this hypothesis is given here because the enzyme kinetic hypothesis of membrane transport has been extensively reviewed in the literature (Epstein, 1973; Hodges, 1973; Nissen, 1974; Clarkson and Hanson, 1980; Nissen et al., 1980; Fageria, 1984). According to Epstein and Hagen (1952), transport of an ion into a plant cell may be analogous to the relationship between the binding of a substrate to an enzyme and the release of its products after catalysis. The overall sequence of events during an enzyme-catalyzed reaction, SEP, may be depicted as shown below (Segal, 1968):

$$E + S \Leftrightarrow ES \Leftrightarrow EX \Leftrightarrow EY \Leftrightarrow EZ \Leftrightarrow E - P \Leftrightarrow P + E$$

The enzyme (E) first combines with the substrate (S) to form an enzyme–substrate complex (ES). On the surface of the enzyme, the substrate may go through one or more transitional forms (X, Y, Z) and finally be converted to the product (P). The product then dissociates, allowing the free enzyme (E) to begin again.

Ion uptake by plants follows a hyperbolic relationship with increasing concentrations (up to about 200 mmol m^{-3}) in the growth medium (Ingestad, 1982) and can be explained by Michaelis–Menten kinetics. The uptake rate at a given concentration can be predicted with the help of the following equation:

$$V = \frac{V_{max} C_i}{K_m + C_i}$$

where

V_{max} is the maximum velocity
C_i is the concentration of the ion in the growth medium
K_m is the Michaelis constant, equal to the substrate ion concentration giving half the maximal rate of uptake (Figure 3.7)

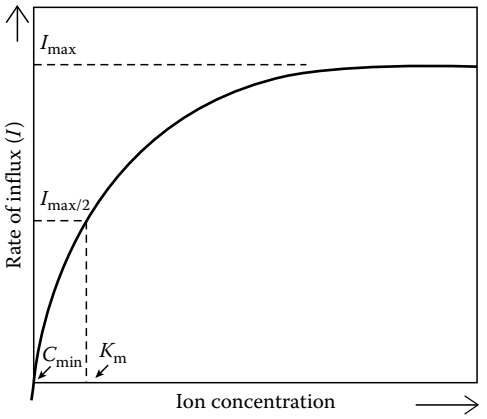

FIGURE 3.7 Relationship between ion concentration and influx rate.

A small value for K_m implies a high affinity between the ion and the carrier. If the uptake rate and concentration are plotted as reciprocals, a straight line is frequently obtained. Extrapolation of this line gives an intercept at $1/V_{max}$; the concentration at half-maximal velocity corresponds to K_m. This method of calculating K_m is known as the Lineweaver–Burk plot method. An alternative procedure is to plot the rate of uptake (V) against V/C and obtain V_{max} and V_{max}/K_m by extrapolation of the experimentally determined slope to the ordinate and abscissa, respectively (Clarkson, 1974). This method is known as the Hofstee plot method.

Claasen and Barber (1976) described the ion absorption isotherm in terms of I_{max}, K_m, and E (Figure 3.7) and proposed the following equation:

$$I_{max} = \frac{I_{max} C_i}{K_m + C_i} - E$$

Since the uptake rate was zero at a concentration above zero, the line was extended to the ordinate, giving negative uptake at zero ion concentration, which was termed efflux (E) from the root (Barber, 1995). Nielsen and Barber (1978) made a further modification by using the concentration in solution where the net influx reaches zero, rather than E, as the third point describing the lower end of the absorption curve. This value was termed C_{min} and the equation written as follows:

$$I_{max} = \frac{I_{max}(C_i - C_{min})}{K_m + C_i - C_{min}}$$

Values of I_{max}, K_m, and C_{min} for some nutrients and plant species are presented in Table 3.5. It should be kept in mind that ion uptake kinetics values vary with plant age, nutrient concentration, temperature, root morphology, plant demand for nutrients, and analytical techniques.

Hai and Laudelot (1966) and Fageria (1973, 1976) proposed a continuous-flow technique to measure nutrient uptake kinetics. The basic principle of the continuous-flow system is that the rate of nutrient uptake (U) is equal to the product of the flow rate (F) and the difference between the concentration of the solution entering the system (C_0) and of the outgoing solution (C_s). A mathematical equation can be written as follows:

$$U = C(C_0 - C_s)$$

TABLE 3.5
Nutrient Uptake Kinetics Values of Intact Crop Plants

Crop	Plant Age (Days)	Nutrient	I_{max} (nmol m^{-2} s^{-1})	K_m (μmol L^{-1})	C_{min} (μmol L^{-1})	Reference
Wheat	20–38	P	1.4	6	—	Anghinoni et al. (1981)
	20–40	K	7.0	7	—	Barber (1995)
	30–40	Ca	1.6	5		Barber (1995)
	20–40	Mg	0.4	1		Barber (1995)
Corn	18–20	NO_3	10	3	4	Edwards and Barber (1976)
	14–28	P	4	3	0.2	Jungk and Barber (1975)
	18	K	40	16	1	Baligar and Barber (1978)

The rate of ion uptake, expressed in μg h^{-1} g^{-1} root weight (may be fresh or dry), is calculated by the following formula:

$$\text{Rate of ion uptake} = \frac{(1 - C_s/C_0) \times F \times C}{\text{Root weight}}$$

where

C_s is the concentration of the outgoing solution
C_0 is the concentration of the ingoing solution
C is the concentration of the stable ion in the nutrient solution (ppm or μmol L^{-1})

In the continuous-flow culture technique, flow rate through the system is one of the most important parameters to be considered in ion uptake studies. Edwards and Asher (1974) have discussed the significance of solution flow rate in flowing culture experiments and concluded that the actual flow rate required for a particular experiment will depend upon the nature and concentration of the ion, age of the plant, efficiency of roots in absorbing the test ion, and conditions of the experiment. The technical and methodological aspects of this technique can be found in many publications (Edwards and Asher, 1974; Fageria, 1974; Asher and Edwards, 1983; Callahan and Engel, 1986; Wild et al., 1987). The concentrations of nutrients used in flowing culture solution are much lower than those in non-flowing solutions (Table 3.6).

The response of the I_{max} and K_m of a transport process to physical and metabolic factors can undoubtedly provide some insight into the general nature of the processes moving ions across membranes (Clarkson, 1984). The specificity of the mechanisms involved can be inferred from the effect of competing ions on V_{max}. Studies of this kind by Epstein (1966) led to the conclusion that there were two sets of binding sites, one with affinity for K^+ and another with affinity for Na^+, as well. At low concentrations of K^+, Na^+ had no effect on V_{max} of K^+, but at higher concentrations of K^+, I_{max} was increasingly depressed by increasing Na^+.

Epstein and coworkers at the University of California at Davis found the relationship between ion concentration and uptake rate to be more complex when the concentration was varied over a large range. They attributed the kinetics to the simultaneous functioning of two different carriers for the same ion and suggested that both mechanisms are located in the plasmalemma (Figure 3.8). On the other hand, Laties and coworkers at the University of California at Los Angeles suggested that the mechanisms are in series, one in the plasmalemma and one in the vacuolar membrane or tonoplast. Later, Nissen (1971, 1974) suggested that uptake mechanisms remain unchanged over the entire concentration range but the characteristics of uptake change at certain discrete external concentrations. Nissen (1973) and Nissen et al. (1980) reexamined ion absorption data for many plant species and came to the conclusion that ion uptake in higher plants can be described by multiphasic uptake

TABLE 3.6
Composition of Flowing Culture Solution

Nutrient	Islam et al. (1980)	Fageria (1976)
	Macronutrients (μM)	
Nitrogen (NO_3^-)	250	193
Nitrogen (NH_4^+)	—	227
Phosphorus	15	31
Potassium	250	250
Calcium	250	125
Magnesium	10	41
Sulfur	261	27
	Micronutrients (μM)	
Manganese	0.25	2.0
Zinc	0.50	0.17
Copper	0.10	0.2
Boron	3.0	9.7
Iron	20.0	9.5
Molybdenum	0.02	0.004
Chlorine	5.0	46

Source: Fageria, N.K., *J. Plant Nutr.*, 28, 1975, 2005.

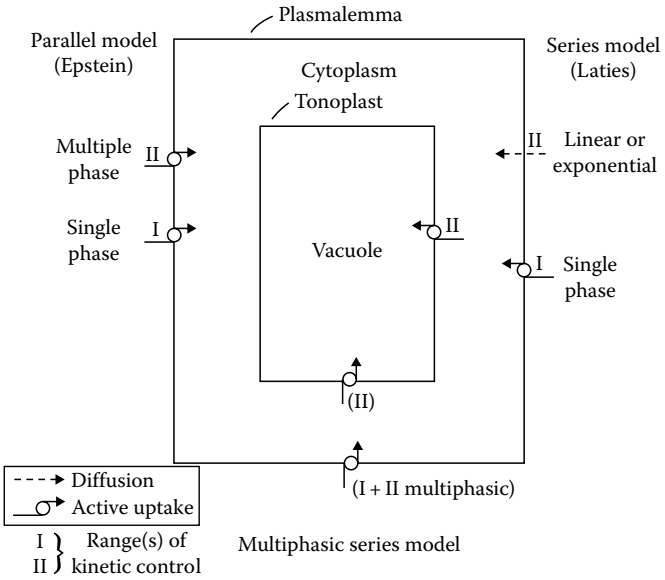

FIGURE 3.8 Ion transport models. (Adapted from Nissen, P., *Physiol. Plant.*, 28, 113, 1973.)

mechanisms and that this accounts for the apparently contradictory evidence for the parallel and the series models (Figure 3.8). Further, Nissen (1991) describes kinetic models as a single diffusion model and multiphasic model. To calculate ion uptake kinetics, he gave a formula for each model (Table 3.7) and discussed their advantages and shortcomings in ion uptake kinetic studies (Nissen, 1991). In contrast to other kinetic models, which may all be termed continuous, the multiphasic

TABLE 3.7
Kinetic Models for Solute Uptake in Plants

Model	Formula[a]
Single + diffusion	$V = \frac{V_{max}S}{K_m + S} + kDS$
Dual	$V = \frac{V_{max1}S}{K_{m1} + S} + \frac{V_{max2}S}{K_{m2} + S}$
Dual + diffusion	$V = \frac{V_{max1}S}{K_{m1} + S} + \frac{V_{max2}S}{K_{m2} + S} kDS$
Multiphasic	$V = \frac{V_{max_n}S}{K_{m_n} + S}$ (for phase n)

Source: Adapted from Nissen, P., *Plant Roots: The Hidden Half*, Marcel Dekker, New York, 1991.

[a] S, solute concentration; V, uptake rate; V_{max}, maximum uptake rate; K_m, Michaeli's constant; kD, diffusion constant.

model predicts a discontinuous relationship between ion concentration and rate of uptake. Fitting of kinetic models to data for different ions and for a variety of plants and tissue shows that the fit to the multiphasic model is better than the fit to any of the continuous models which have been proposed (Nissen et al., 1980).

3.3.6 Use of Solution Culture in Ion Uptake Studies

In ion uptake or kinetics studies, solution culture techniques are generally used because in solution culture, variability in nutrient concentrations and other environmental factors can be easily controlled. In addition, growing plants in solution culture is an important and very old technique in mineral nutrition studies. Some important discoveries in mineral nutrition have been made using solution culture techniques such as discovery of essentiality of nutrients. Although the famous experiments of Woodward (1699) represent the earliest recorded use of solution culture techniques to study the growth of plants, the experiments of Saussure (1804) are probably more significant in that they involved the first use of nutrient solutions of known initial composition, prepared by dissolving various salts in distilled water. Subsequently, Sachs (1860) and Knop (1865) showed that plants could be grown to maturity in simple solution culture systems not very different from those currently used in many plant research laboratories throughout the world (Asher and Edwards, 1983).

In addition to the convenience of use of solution culture for ion uptake studies, solution culture is useful for developing deficiency symptoms of nutrients essential for plant growth. These symptoms can be used as a guide to identify nutritional disorders in crop plants under field conditions. In addition to deficiency symptoms, it is also possible to develop toxicity symptoms for some elements. The symptoms can be used to identify toxicities and suggest possible corrective measures. Examples include Al toxicity in acidic soils, iron toxicity in flooded rice, and soil salinity problems in saline soils.

Critical tissue concentrations for the diagnosis of nutrient deficiencies and toxicities are frequently established from water culture or sand culture experiments. Although many plant and environmental factors have been shown to affect measured critical concentrations (Bates, 1971), it has been widely assumed that critical tissue concentrations are comparatively stable plant characteristics unlikely to be affected by temporal variation in the external supply of the element concerned

TABLE 3.8
Nutrient Solution Composition Used in the Solution Culture Studies

Nutrient	Hoagland and Arnon (1950)	Johanson et al. (1957)	Andrew et al. (1973)	Clark (1975)	Yoshida (1976)
NO_3^- (mM)	14.0	14.0	2.00	7.26	2.21
NH_4^+ (mM)	1.0	2.0	—	0.90	0.64
P (mM)	1.0	2.0	0.07	0.07	0.29
K (mM)	6.0	6.0	1.10	1.80	1.02
Ca (mM)	4.0	4.0	1.00	2.60	1.00
Mg (mM)	2.0	1.0	0.50	0.60	1.64
S (mM)	2.0	1.0	1.50	0.50	—
Mn (μM)	9.1	5.0	4.60	7.00	9.00
Zn (μM)	0.8	2.0	0.80	2.00	0.15
Cu (μM)	0.3	0.5	0.30	0.50	0.16
B (μM)	46.3	25.0	46.30	19.00	18.50
Mo (μM)	0.1	0.1	0.10	0.60	0.50
Fe (μM)	32.0	40.0	17.90	38.00	36.00
Cl (μM)	—	50.0	—	—	

(Asher and Edwards, 1983). However, care should be taken when such results are extrapolated to field conditions because, under field conditions, variability in environmental factors is quite great, which may influence nutrient concentrations in plant tissues. Compositions of nutrient solutions commonly used in hydroponic techniques are given in Table 3.8. In preparing nutrient solutions, all the chemicals should be reagent grade. Table 3.9 presents commonly used chemicals for preparing nutrient solutions. The iron is generally chelated with EDDHA, HEDTA, and EDTA.

According to Chaney and Bell (1987), the Fe-chelate of choice for solution culture of dicots is FeEDDHA, for grasses the recommended chelate is FeHEDTA. Commercial FeEDDHA or FeHEDTA is neither pure enough for use in controlled solution experiments nor easily available in developing countries. Therefore, one should purchase pure chelates and make one's own solutions. The solutions of these chelates are difficult to prepare. Therefore, methods for their preparation are given in Fageria (2005) and in Appendix 3.A.

Chelators added at sufficiently high concentrations to hydroponic solution can induce micronutrient deficiencies by chelating Cu, Zn, Mn, and Fe, making the metals unavailable to plants (Fageria and Gheyi, 1999). This loss in metal bioavailability can be counteracted by increasing the amount of metal in solution. Hydroponic solutions that have a chelator concentration greater than the sum of the concentrations of Fe, Cu, Zn, Mn, Co, and Ni are called chelator-buffered solutions, and they are usually designed to also prevent Fe precipitation (Chaney et al., 1989). Chelator-buffered solutions offer more precise control of micronutrient phytoavailability than do conventional hydroponic solutions because, in the buffered solutions, there is a greater range in the total metal concentration from deficiency to toxicity, and the free metal ion activity decreases only a small amount during plant uptake of metals because metal activities are buffered (Bell et al., 1991).

3.3.6.1 pH of Solution Culture

In solution culture experiments, it is important both to control solution pH and maintain a stable supply of nutrients. In general, pH shifts in nutrient solutions are likely to be greater than in soils because of the lack of an exchange complex to adsorb or desorb hydrogen ions. The principal factor that leads to change in nutrient solution is unequal absorption of cations and anions. Nitrogen

TABLE 3.9
Commonly Used Reagent Grade Chemicals for Nutrient Solution

Nutrient	Reagent	1 M Solution (g L^{-1})
Nitrogen	$(NH_4)_2SO_4$	132.0
Nitrogen	NH_4NO_3	80.0
Phosphorus	$NaH_2PO_4 \cdot 2H_2O$	156.0
Phosphorus	KH_2PO_4	136.0
Potassium	KCl	74.6
Potassium	KNO_3	101.1
Potassium	K_2SO_4	174.2
Calcium	$CaCl_2 \cdot 2H_2O$	147.0
Calcium	$Ca(NO_3)_2 \cdot 4H_2O$	236.2
Calcium	$CaSO_4 \cdot 2H_2O$	172.1
Magnesium	$MgSO_4 \cdot 7H_2O$	246.3
Manganese	$MnCl_2 \cdot 4H_2O$	197.9
Manganese	$MnSO_4 \cdot 4H_2O$	169.0
Zinc	$ZnSO_4 \cdot 7H_2O$	287.4
Zinc	$ZnCl_2$	136.3
Copper	$CuSO_4 \cdot 5H_2O$	249.5
Copper	$CuCl_2 \cdot 2H_2O$	170.4
Boron	H_3BO_3	61.8
Molybdenum	$(NH_4)_6Mo_7O_{24} \cdot 4H_2O$	1235.6
Molybdenum	$Na_2MoO_4 \cdot 2H_2O$	241.9
Iron	$FeCl_3 \cdot 6H_2O$	270.0
Iron	$FeSO_4 \cdot 7H_2O$	278.0
Iron	$Fe(NO_3) \cdot 9H_2O$	404.0

Source: Fageria, N.K., *J. Plant Nutr.*, 28, 1975, 2005.

is absorbed in large quantity and the form in which this element is supplied exerts a great influence on pH change. The absorption of more anion such as NO_3^- can liberate the OH ions into the rhizosphere, increasing its pH. If more cations such as NH_4^+ are absorbed, pH is decreased due to liberation of H^+ ions into the growth medium. Trelease and Trelease (1935) showed in water culture experiments with wheat that by varying the NO_3^-/NH_4^+ ratio, they could cause the pH to increase, decrease, or remain about constant. Crop species differ in their effects on nutrient solution pH due to their different nutrient absorption capacities. Even cultivars within a crop species can modify solution pH in different ways. It has been consistently observed that non-nodulated jackbeans (*Canavalia ensiformis*) reduce the pH of the nutrient solution markedly with time, even when all the nitrogen is supplied in the NO_3^- form (Asher and Edwards, 1983).

Appropriate pHs for nutrient solutions are certainly different from those for soils. The range reported in literature for conducting solution culture experiments varies from pH 5 to 7. For example, Yoshida et al. (1976) reported that for rice, the pH of the nutrient solution should be maintained around 5.0. However, rice plants can grow well in nutrient solution even at pH 4.0 provided all essential nutrients are maintained at adequate levels (Fageria, 1989). Hohenberg and Munns (1984) studied the effect of pH on nodulation of cowpea in nutrient solution and concluded that pH 5.3 ± 0.3 was superior in nodulation as compared to pH of 4.4 ± 0.2, although there were differences among cultivars in relation to pH tolerance.

For many years, researchers have used nutrient solutions to study plant nutrition, and many different approaches have been used to either control solution pH or allow it to be modified by the plant.

Some have maintained the pH of nutrient solutions by adjusting the pH with HCl or NaOH (Peaslee et al., 1981; Ben-Asher et al., 1982; Itoh and Barber, 1983; Miyasaka and Grunes, 1990; Bell et al., 1991; Teyker and Hobbs, 1992). Others have allowed the pH to vary without constraint (Brown and Jones, 1976). To maintain a desired pH, the pH of the culture solution can be adjusted to the desired level every second day with either by 1 N NaOH or 1 N HCl.

Researchers have also studied the influence of various percentages of NO_3^- to NH_4^+ and N concentration on N absorption, assimilation, growth, and yield of lima beans in nutrient solution. These authors adjusted initial solution pH to 6.6, and change in pH due to nutrient absorption was not adjusted during experimentation; so, the influence of pH on N uptake at weekly intervals could be evaluated (McElhannon and Mills, 1978).

Often, nutrient solution pH has little effect on plant growth. For example, Breeze et al. (1987) found that the increase of dry weight of white clover over a 20 day period, whether fixing atmospheric nitrogen or dependent on NO_3^- in solution, was not significantly lower at pH 4.0 than at pH 5.0, 6.0, or 7.0.

Islam et al. (1980) used flowing nutrient solutions to study the effects of solution pH on the growth of six species: ginger, cassava, tomato, common bean, wheat, and maize. Optimum yields were found at solution pH of about 5.5. Yields of ginger and tomato were not significantly changed at higher pH values whereas yields of the other four species were depressed. Edmeades et al. (1991) reported that increasing the nutrient solution pH from 4.7 to 6.0 had no significant effect on the yield of the temperate grasses examined but significantly decreased yields of paspalum and veld grass.

In the author's opinion, all crops can be grown in nutrient solution satisfactorily with a pH value of around 5.5. At pH values higher than 5.5, there is always a possibility of precipitation of micronutrients, thereby reducing their availability. In studies of Al toxicity, solution culture pH should not be more than 4.0 to avoid precipitation of Al. However, two methods of pH control that have been shown to have promise are ion exchange resins (Checkai et al., 1987) and the organic buffer, 2-(N-morpholino) ethanesulfonic acid (MES) (Wehr et al., 1986). Miyasaka et al. (1988) compared an unbuffered nutrient solution titrated once or twice a day, with solution buffered either by the organic buffer, MES, or by an ion exchange system using a weakly acidic cation exchange resin loaded with Ca, Mg, K, and H. These authors recommended that among the pH buffer methods studied, 1 mM MES method is recommended as a pH buffer for the hydroponic culture for winter wheat. Five millimolar MES gave the most consistent control of solution pH; however, it also inhibited Zn accumulation by wheat. Imsande and Ralston (1981) found that 1–2 mM MES had excellent buffering capacity, did not interfere nutritionally with soybean growth, and did not impede N_2 fixation.

However, Rys and Phung (1985) found that MES at 9 and 12 mM concentrations resulted in reduced growth of *Trifolium repens* L., which is dependent on symbiosis to provide N. They suggested that the N-fixing ability of nodules was impaired by high levels of MES. Wehr et al. (1986) considered MES to be the most useful buffer in the pH range of 5.0–6.5 for growth of algae because of its biological inertness, high buffering capacity, and minimal metal-complexing ability. However, Clark (1982) stated that, "buffered solutions often induce more complications than original solutions." More research is needed to understand the effects of buffering reagents on nutrients uptake and plant growth.

3.3.7 Ion Absorption Measurement

Ion uptake measurement is usually measured by tracer techniques in excised roots. Measuring rates of uptake in this way tends to ignore the large amount of ions transported across the root to the xylem and finally to the shoot. In practice, only a small fraction of the nutrients absorbed is retained in the roots and the major part is exported to the shoots (Asher and Ozanne, 1967; Loneragan and Snowball, 1969). Therefore, in ion absorption measurements, roots as well as shoots should be taken into account.

One way to measure the rates of absorption of nutrients by plant roots is to estimate the changes in nutrient content of root and shoot by chemical analysis. The values obtained by this procedure are necessarily averaged over several days but are nonetheless useful indications of the scale of the absorption process (Pitman, 1976). Equations for analyzing uptake by plants have been presented and discussed by many workers (Williams, 1948; Loneragan, 1968; Pitman, 1976). The net rate of ion uptake relative to root weight (U_R) is equal to ($1/W_R$) dm/dt, where W_R is root weight and M is the nutrient content of the plant (Pitman, 1976). An average rate of uptake is therefore

$$U_R = \frac{1}{\overline{W}_R} \frac{M_2 - M_1}{t_2 - t_1} \tag{3.1}$$

where $\overline{W}_R$ is average root weight for young plants growing exponentially.

$$W_R = \frac{(W_{R2} - W_{R1})}{In\,(W_{R2}/W_{R1})}$$

Hence, in this case,

$$U_R = \frac{M_2 - M_1}{(t_2 - t_1)\,(W_{R2} - W_{R1})} In\left(\frac{W_{R2}}{W_{R1}}\right) \tag{3.2}$$

Note that if the relative content M/W is constant (X), then,

$$U_R = X \frac{W}{W_R} \frac{In\,(W_{R2}/W_{R1})}{t_2 - t_1} = X \frac{W}{W_R} R \tag{3.3}$$

where R is relative growth rate, provided W/W_R is constant.

Note that U_R is an average made up of uptake to each part of the plant, e.g.,

$$U_R = U_{Ra} + U_{Rb} + \cdots + U_{Rn} \tag{3.4}$$

where $a \ldots n$ refer to different parts of the plant, and if X_n is constant, then,

$$U_n = \frac{W_n}{W_R} X_n R_n \tag{3.5}$$

Alternatively, if X_n is not constant, individual U_{Rn} values can be calculated as for Equation 3.1 and summed to give total uptake to the shoot (Pitman, 1976).

3.4 SUMMARY

Nutrient absorption by plants is a dynamic and complex process and kinetics is usually more important than thermodynamics in describing this system. The rate of nutrient absorption by a root depends on the nutrient supply to the root surface, active absorption by roots, and plant demand for

nutrients. Nutrients are transported to the root by mass flow, diffusion, and root interception. After reaching the root surface, nutrients move into the xylem through various root cells; from the xylem, ions are transported to the growing organs in the shoot for metabolic processes. Ion concentrations in the cell sap are often much higher than in the outside medium, and ions frequently have to move against a concentration gradient. In this process, energy is required and is supplied through root respiration. The kinetics of ion absorption in roots is similar to the kinetics of enzyme-catalyzed reactions. This kinetic information provides insight into the nature of ion carriers. Most ion uptake studies have been done in short-duration solution culture experiments using excised roots. These studies need to be conducted for a longer duration using intact plants in soil to obtain experimental results with more practical applicability.

APPENDIX 3.A

3.A.1 Preparation of FeEDDHA Solution

To prepare FeEDDHA solution for solution culture experiments, EDDHA salt, ferrous sulfate or ferric nitrate, and KOH or NaOH salts are required. All these salts should be reagent grades.

1. Prepare 8 mM solution of EDDHA by dissolving 2.972 g L^{-1} in deionized water. The currently available EDDHA salt is about 97% pure with formula weight of 360.37 g mol^{-1}.
2. Prepare 8 mM solution of ferrous sulfate ($FeSO_4 \cdot 7H_2O$) or ferric nitrate ($Fe(NO_3)_2 \cdot 9H_2O$). In case of $FeSO_4 \cdot 7H_2O$ (FW 278.02 g mol^{-1}, 99% pure), 2.25 g L^{-1} reagent is required. In case of $Fe(NO_3)_2 \cdot 9H_2O$ (FW 404 g mol^{-1}, 100% pure), 3.23 g L^{-1} of salt is required.
3. Prepare 32 mM solution of KOH or NaOH. In case of KOH with formula weight of 66 g mol^{-1} and 100% pure, 2.11 g L^{-1} salt is required. In case of NaOH with formula weight of 40 g mol^{-1}, 1.28 g L^{-1} of reagent is required for a solution of 32 mM.
4. Add 32 mM KOH or NaOH solution to 8 mM EDDHA solution and stir for 30–60 min.
5. Add ferrous or ferric 8 mM solution to mixed EDDHA and KOH or NaOH solution.
6. Adjust pH 6–7 by KOH or HCl. Stir overnight at >50°C. Then filter with Whatman filter paper no. 42 to remove $Fe(OH)_3$.
7. Store in brown bottle in refrigerator.
8. 2 L of this solution contains 4 mM or 224 ppm of Fe^{3+}. One can use a Fe^{2+} salt to prepare the Fe^{3+} chelates, but one should recognize that the ligand will catalyze oxidation of the Fe^{2+} if oxygen is present.

3.A.2 Preparation of FeHEDTA Solution

To prepare 1 L of Fe-chelate solution, 30 mM solution of HEDTA and 30 mM of ferrous sulfate or ferric nitrate solutions are required.

1. Prepare 30 mM solution of HEDTA by dissolving 11.52 g L^{-1} in deionized water. The commercially available HEDTA has formula weight of about 380.24 g mol^{-1} with 99% purity.
2. Ferrous sulfate solution ($FeSO_4 \cdot 7H_2O$, FW 278.02 g mol^{-1} with 99% purity): add 8.42 g L^{-1} to get 30 mM solution. If ferric nitrate is used, it generally has 404 g mol^{-1} formula weight, 12.12 g L^{-1} of deionized water is required to give 30 mM solution.
3. Add ferrous sulfate or ferric nitrate solutions to HEDTA solution. Stir for 30–60 min at >50°C. Then filter through Whatman filter paper no. 42. Store in brown bottle and keep in a refrigerator. This 2 L solution has 15 mM or 840 ppm Fe solution.

3.A.3 Preparation of FeEDTA Solution

To prepare FeEDTA solution, sodium salt of EDTA and ferrous sulfate along with NaOH solution is used. To prepare 1 L of FeEDTA solution, the following composition and procedure should be adopted:

1. Dissolve 33.2 g NaEDTA salt ($C_{10}H_{14}N_2Na_2O_8 \cdot 2H_2O$ FW 372.24 g mol^{-1}) in about 200 mL of deionized water.
2. Make an 89.2 mL solution of 1 N NaOH.
3. Dissolve 29.4 g of $FeSO_4 \cdot 7H_2O$ in about 100 mL of deionized water.
4. Mix NaEDTA and NaOH solutions slowly and stir. Then, mix this solution with $FeSO_4 \cdot 7H_2O$ solution. Leave this solution overnight in a dark ambience. Next day, complete the volume to 1 L. This solution will contain 106 mM or 5936 ppm Fe. According to Novais et al. (1991), FeEDTA solution can also be prepared by mixing 14.1 g of Na_2 EDTA and 10.3 g of $FeCl_3 \cdot 6H_2O$, diluted separately in about 300–400 mL of deionized water and then mixed together to make a volume of 1 L. This solution contains 38 mM Fe. Care should be taken while chelating iron used in nutrient solution.

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4 Diagnostic Techniques for Nutritional Disorders

4.1 INTRODUCTION

A rapidly increasing world population demands ever-increasing food production. In this context, modern agriculture must use every available tool to produce adequately and efficiently. Further, public concern about environmental quality and the long-term productivity of agroecosystems has emphasized the need to develop and implement management strategies that maintain soil fertility at an adequate level without degrading soil and water resources (Fageria, 2009). Therefore, nutrient inputs must be supplied to replace those removed from the soil and to achieve higher yields from a limited land resource. To meet these demands, nutrient needs must be accurately identified and nutrients applied to achieve maximum benefit from their use.

Diagnostic techniques are used to identify nutrient deficiencies, toxicities, or imbalances in the soil–plant system. Nutrient deficiency can occur when a nutrient is insufficient in the growth medium and/or cannot be absorbed and assimilated by plants due to unfavorable environmental conditions. Table 4.1 shows soil conditions associated with nutrient deficiencies. Similarly, nutrient or elemental toxicities may occur due to excess, imbalance, and unfavorable environmental conditions.

Worldwide, one of the major problems limiting crop production is nutrient deficiency. As much as 50% of the increase in crop yields worldwide during the twentieth century was due to the adoption of chemical fertilizers (Fageria and Baligar, 2005a; Fageria, 2009). In the twenty-first century, chemical fertilizers will play a major role in increasing crop yields, mainly due to limited land and water resources available for crop production and declining trends in crop yields globally (Fageria et al., 2008a). Furthermore, at least 60% of the world's arable lands have mineral deficiencies or elemental toxicity problems, and on such soils fertilizers and lime amendments are essential for achieving improved crop yields (Fageria and Baligar, 2008). In fact, soil infertility (natural elemental deficiencies or unavailability) is probably the single most important factor limiting crop yields worldwide. Nutrient or elemental disorders limit crop production in all types of soils around the world. To obtain good yields of crops, nutrient disorders must be corrected. The first step in this direction is to identify the nutritional disorder. The four most common methods of identifying nutritional deficiencies, toxicities, or imbalances are soil analysis, plant analysis, visual symptoms, and crop growth response. Each method has its advantages and disadvantages, and it is difficult to say which is best. One or a combination of all techniques can be used to identify nutritional disorders in the soil–plant system (Fageria and Baligar, 2005b). A detailed discussion of these diagnostic techniques is given in this chapter.

4.2 SOIL TESTING

Soil testing has become an essential and integrated part of soil management in present-day agricultural systems (Indiati et al., 2002; Jacobson et al., 2002). In addition to being a useful diagnostic tool for evaluating soil fertility for fertilizer recommendations, soil testing also plays an important role in the prevention of environmental degradation by providing guidelines for minimizing loss of nutrients to surface and groundwaters (Menon and Chien, 1995). According to Jones (1985), soil testing probably has a greater agronomic application than plant analysis for annual row crops, but

TABLE 4.1
Soil Conditions Inducing Nutrient Deficiencies for Crop Plants

Nutrient	Conditions Inducing Deficiency
N	Excess leaching with heavy rainfall, low organic matter content of soils, burning the crop residue
P	Acidic, organic, leached, and calcareous soils, high rate of liming
K	Sandy, organic, leached, and eroded soils; high liming application, intensive cropping system
Ca	Acidic, alkali, or sodic soils
Mg	Similar to calcium
S	Low organic matter content of soils; use of N and P fertilizers containing no sulfur, burning the crop residue
Fe	Calcareous soils; soils high in P, Mn, Cu, or Zn; high rate of liming
Zn	Highly leached acidic soils, calcareous soils, high levels of Ca, Mg, and P in the soils
Mn	Calcareous silt and clays, high organic matter, calcareous soils
B	Sandy soils, naturally acidic leached soils, alkaline soils with free lime
Mo	Highly podzolized soils; well-drained calcareous soils
Ni	Soil parent materials low in Ni and erosion of top soil layer

for perennial horticulture crops, plant analysis is the more significant testing procedure. In a broad sense, soil testing is any chemical or physical measurement that is made on a soil (Melsted and Peck, 1973). The main objective of soil testing is to measure soil nutrient status and lime requirements in order to make fertilizer and lime recommendations for profitable farming. Soil testing is an important tool in high-yield farming, but it produces the best results only when used in conjugation with other good farming practices. "There is good evidence that the competent use of soil tests can make a valuable contribution to the more intelligent management of the soil." This statement was made by the U.S. National Soil Test Workgroup in its 1951 report and is still applicable today (Fageria and Baligar, 2005b).

Soil testing includes collection of soil samples, sample preparation, laboratory analysis, calibration and interpretation of the tests, and recommendations. Since the late 1940s, soil testing has been widely accepted as an essential tool in formulating sound lime and fertilizer management programs. Currently, soil testing is the most widely used practice for soil fertility evaluation and management. Routine soil analysis is done for pH, P, K, Ca, and Mg, and where soil acidity is a problem, Al is also determined. Other determinations, such as organic matter and micronutrients, are performed under specific conditions but are not done routinely.

The use of soil analysis as a fertilizer recommendation method is based on the existence of a functional relationship between the amount of nutrient extracted from the soil by chemical methods and crop yield. When a soil analysis test shows a low level of a particular nutrient in a given soil, application of that nutrient can be expected to increase crop yields. Generally, nutrient analysis is arbitrarily classified as very low, low, adequate, high, and excess. Under very low nutrient levels, relative crop yields are expected to be less than 70% of those obtained under adequate nutrient levels, and large applications of fertilizer are required to build soil fertility. After the application of the nutrient, growth response is expected to be dramatic and profitable (Fageria and Baligar, 2005b). Under the low fertility level, relative yield is expected to be 70%–90% of the maximum, and annual fertilizer application is necessary to produce maximum response and increase soil fertility. In this situation, the increased yields usually justify the cost of fertilization. When soil analysis tests show adequate nutrient levels, relative crop yields are expected to be 90%–100%. Normal annual fertilizer applications are usually needed to replace nutrients removed in crop yields and produce maximum yields. In this case more fertilizer may increase yields slightly, but the added yield would not pay back the expense of the additional fertilizer. Under high levels of nutrient, no increases in yields are expected, but small applications may be recommended to maintain soil fertility. When soil tests show very high or excess levels of a nutrient, yields may be reduced

due to toxicity or imbalances of nutrients. Under this situation there is no need to apply fertilizers until levels drop back into the low range.

To obtain the relationships between soil nutrient levels and crop yields, it is necessary to conduct fertilizer yield trials at several locations within a given agroecological region for different crops. Some specific recommendations for soil analysis are summarized here.

4.2.1 Soil Sampling

A reliable fertilizer or lime recommendation depends on a soil sample representative of the area from which it was taken, an accurate laboratory analysis, and correct interpretation of the laboratory results. The greatest source of error is usually the soil sample itself. Since soil is extremely heterogeneous, it is important that the sample tested be truly representative of the area sampled. A common error in soil sampling occurs when the top few centimeters of soil are dry and are not included in the normal sampling procedure. Most of the immobile nutrients remain in the top layers (Table 4.2), and if a few centimeters of the top layer are not collected, soil analysis results will show abnormally low values. During sampling, surface and subsurface soil should be kept separate for individual analysis and interpretation. Sampling depth is dependent on nutrient mobility and crops to be planted. Mobile nutrients, such as NO_3^-, SO_4^{2-}, and borates should be sampled to a depth of about 60 cm, and samples must be taken when biological activity is low (Sabbe and Marx, 1987). For immobile nutrients like P, K^+, Ca^{2+}, and Mg^{2+}, sampling to tillage depth can give satisfactory results. For a pasture crop a 10 cm depth is normally sufficient, whereas for field crops a depth of 15–20 cm is desired.

Sampling patterns for rectangular and triangular fields are described by Sabbe and Marx (1987), and are presented in Figure 4.1. The soil samples should be taken in a zigzag pattern, and this pattern can be formed on the basis of the number of samples desired in a given area. For example, in a rectangular field for which 10 samples are desired, the field can be divided into 10 equal blocks. In addition, since each block has dimensions, a and $2B$, the distance and direction for the zigzag pattern are defined. The distance is $(a^2 + B^2)^{1/2}$ and the direction is given by θ = tangent (B/a). Once the sampling plan has been devised, the actual samples may be collected by the shortest route. Similarly, in a triangular field, the zigzag pattern can be evolved by defining the first direction as θ = tangent(B/a) and the distance as $(a^2 + B^2)^{1/2}$. The third sampling location

TABLE 4.2
Extractable P, K, and Ca + Mg at Different Depths in an Oxisol of Central Brazil[a]

Soil Depth (cm)	P (mg kg^{-1})	K (mg kg^{-1})	Ca + Mg (cmol kg^{-1})
0–20	1.17	30	2.37
20–40	0.50	19	0.70
40–60	0.40	16	0.53
60–80	0.37	14	0.56

Sources: Adapted from Fageria, N.K. et al., Influence of phosphate rock sources and rates on rice and common bean production in an Oxisol, in *Plant-Soil Interactions at Low pH*, Wright, R.J. et al. (eds.), Kluwer Academic Publisher, Dordrecht, the Netherlands, 539–546, 1991a; Fageria, N.K. et al., Response of upland rice and common bean to liming on an Oxisol, in *Plant-Soil Interactions at Low pH*, Wright, R.J. et al. (eds.), Kluwer Academic Publisher, Dordrecht, the Netherlands, 519–528, 1991b.

[a] Phosphorus and K were extracted by the Mehlich-1 (0.05 mol L^{-1} HCl + 0.0125 mol L^{-1} H_2SO_4) extracting solution and Ca + Mg with 1 M KCl.

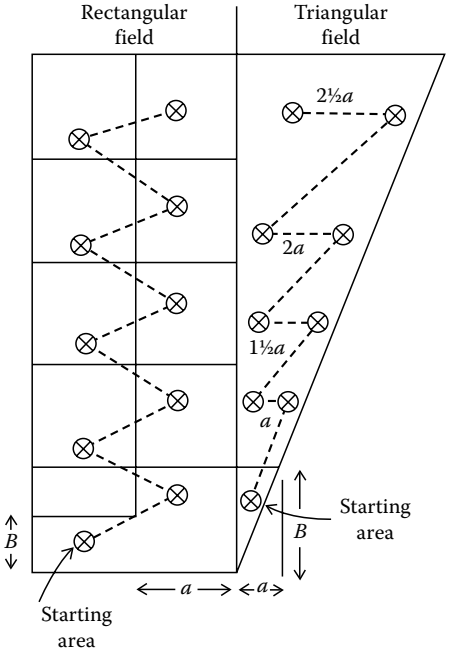

FIGURE 4.1 Zigzag sampling in rectangular and triangular fields. (From Sabbe, W.E. and Marx, D.B., Soil sampling: Spatial and temporal variability, in *Soil Testing: Sampling, Correlation, Calibration, and Interpretation*, Special Publication 21, Brown, J.R. (ed.), Soil Science Society of America, Madison, WI, 1–14, 1987. With permission.)

is distance a from the second. The fourth sampling location is 2*a* to the east and *B* north from the third location. Location 5 is west 1½*a*. Continue the same sequence traveling north *B* and east the same distance as on the preceding westward move, but move an additional *a* east. The difference between the rectangular and the triangular fields lies in the direction and distance to the next sample location (Sabbe and Marx, 1987). A representative soil sample is composed of 15–20 subsamples from a uniform field with no major variations in slope, drainage, or past fertilizer history. If fertilizer has been applied in bands for recent crops, the best way to sample is, if possible, to plough the field before sampling. Alternatively, sampling should occur between the crop rows and well away from the fertilizer bands. If cultivation is intensive, sampling should be done annually to evaluate the fertility status; otherwise, sampling once in a 3 year period is sufficient if the field is planted with one crop per year.

4.2.2 Sample Preparation

After collecting the soil samples, the next step is sample preparation for laboratory analysis. Samples can be dried in moving air but not in heated air. Samples can also be dried at about 50°C in a cabinet-type forced-air dryer for 24–48 h. Wet clay soils may require a longer drying period. However, at no time should samples remain in a heated drier for more than 72 h after becoming dry (less than 2% moisture). Organic soils and soilless mixes are analyzed as received and should not be dried (Jones, 1985). After drying, the samples are ground to pass a 10-mesh (2 mm) screen.

4.2.3 Laboratory Analysis

After sample preparation, laboratory analysis is the next step in a soil testing program. It involves the extraction of nutrients and determination of their concentrations in the extract. Soil testing can

provide a relative index of the quantity of nutrients that plants may utilize from a soil but rarely can provide an absolute measurement (Thomas and Peaslee, 1973). Therefore, soil test values should be expressed as *extractable nutrients* rather than *available nutrients*, even though the quantities of nutrients absorbed by plants may be close to the amount of nutrients extracted by various standard extractants. Ideally, laboratory analysis procedures should be simple, rapid, and reasonably accurate, and extracted nutrients should be correlated with growth or yield of crops under various conditions. To define a suitable extractant, soil test correlation studies must be conducted under greenhouse conditions on a large number of the more important agricultural soils. An ideal extractant would remove approximately the same amount of the element as is removed by the plant. This is never achieved in practice, but a close correlation between plant uptake and the amount of the element extracted chemically is often obtained.

4.2.3.1 pH and Lime Requirement

Soil pH is one of the most important chemical properties used as an index in soil management for crop production. It measures the H^+ ion activity in the soil solution. In measuring soil pH electrometrically, most laboratories use soil/water slurries of 1:1 or 1:3 (vol/vol) and allow them to stand for 1 h or less before reading (Adams, 1984). The use of 0.01 M $CaCl_2$ has also been recommended in pH determinations (Woodruff, 1967). Even though there appear to be good theoretical reasons for measuring soil pH in a 0.01 M $CaCl_2$ solution, failure to do so evidently does not generally result in serious error, as pH values of soils in 0.01 M $CaCl_2$ tend to be slightly lower than, but highly correlated with, those in water (McLean, 1982). The lower value of pH in a $CaCl_2$ solution is related to the displacement of H^+ and Al^{3+} ions from exchange sites by Ca^{2+}.

According to Conyers and Davey (1988), pH values measured in water, 0.01 M $CaCl_2$, and 0.1 M KCl at dilution ratios of 5:1, 2.5:1, and 2:1 (solution:soil) are highly correlated over a wide soil pH range. The relationship between pH in water (pH_w) and pH in 0.01 M $CaCl_2$ (pH_{Ca}) at 2.5:1 solution:soil was found to be $pH_{Ca} = 1.05\ pH_w - 0.9$.

The most common, and in most cases the most effective, way to correct soil acidity has been by applying lime. For example, lime significantly increased grain yields of annual crops grown on an Oxisol (Figure 4.2) and consequently improved nutrient uptake (Table 4.3). The changes in these soil chemical properties with the use of dolomitic lime [$(CaMg(CO_3)_2$] can be explained on the basis of the following equations (Fageria and Baligar, 2005a):

$$CaMg(CO_3)_2 + 2H^+ \leftrightarrow 2HCO_3^- + Ca^{2+} + Mg^{2+}$$

$$2HCO_3^- + 2H^+ \leftrightarrow 2CO_2 + 2H_2O$$

$$CaMg(CO_3)_2 + 4H^+ \leftrightarrow Ca^{2+} + Mg^{2+} + 2CO_2 + 2H_2O$$

The above equations show that acidity neutralizing reactions of lime occur in two steps. In the first step, Ca^{2+} and Mg^{2+} react with H^+ on the exchange complex and H^+ is replaced by Ca^{2+} and Mg^{2+} on the exchange sites (negatively charged particles of clay or organic matter), forming HCO_3^-. In the second step, HCO_3^- reacts with H^+ to form CO_2 and H_2O to increase pH. Soil moisture and temperature and quantity and quality of liming material mainly determine the reaction rate of lime. To get maximum benefits from liming or for improving crop yields, liming materials should be applied in advance of crop sowing and thoroughly mixed into the soil to enhance its reaction with soil exchange acidity (Fageria and Baligar, 2005a).

Soil lime requirement is the amount of liming material required to neutralize the acid cations (H^+ and Al^{3+}) and adjust soil pH to that desired for crop production (Kissel et al., 2007). The main objective of liming acid soils is to increase pH, increase exchangeable Ca and Mg, and

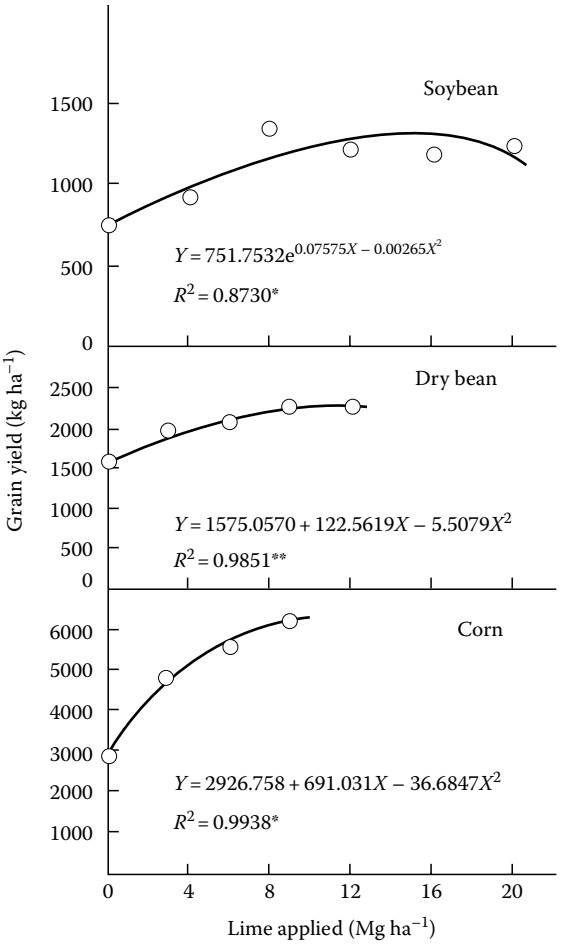

FIGURE 4.2 Influence of lime application rates on grain yield of dry bean, soybean, and corn in Brazilian Oxisol. (Adapted from Fageria, N.K. and Stone, L.F., *Acidity Management of Cerrado and Varzea Soils of Brazil*, National Rice and Bean Research Center of EMBRAPA, Santo Antônio de Goias, Brazil, 1999.)

neutralize Al (Table 4.4). Soil pH indicates whether a soil needs lime, but the quantity of lime required is not determined by soil pH. Several methods are used to determine lime requirements of soils. In the United States, for example, no single method has been officially accepted for estimating lime requirement, and the methods used vary from state to state (Table 4.5). Each method has its advantages and disadvantages, and these are described in detail by Adams (1984). In most cases, the basis of selection of the point to which the soil is to be limed is the pH giving the most favorable plant growth. However, the recommendation may be based on other criteria, such as inactivation of exchangeable Al. In Brazil, liming recommendations are based on soil exchangeable Al, Ca, and Mg. Lime requirement (LR) is calculated using the following formula:

$$\text{LR (Mg ha}^{-1}) = \text{Al} \times 2 + [2 - (\text{Ca} + \text{Mg})]$$

where Al, Ca and Mg are in $cmol_c kg^{-1}$.

The lime requirement computed from the Al, Ca, and Mg contents is based on the assumption that Al toxicity and Ca and Mg deficiencies are the most important growth-limiting factors in acid soils where legumes are not prominent in cropping systems.

TABLE 4.3
Influence of Dolomitic Lime on pH, Ca + Mg, and Al during Cultivation of Upland Rice in an Oxisol of Central Brazil[a]

Lime Level (Mg ha^{-1})	Before Lime Application	18 Days After Sowing	67 Days After Sowing	After First Crop Harvest	After Second Crop Harvest
pH					
0	5	5.0	5.0	5.0	5.0
3	5	5.3	5.4	5.6	5.3
6	5	5.6	5.6	5.8	5.4
9	5	5.9	5.8	6.0	5.7
12	5	6.0	6.0	6.1	5.9
Ca + Mg (cmol kg^{-1})					
0	0.82	1.44	1.49	1.28	1.29
3	0.82	2.17	2.69	2.01	2.10
6	0.82	2.89	3.62	3.31	2.76
9	0.82	3.49	4.29	3.83	3.42
12	0.82	4.00	5.26	3.99	3.92
Al (cmol kg^{-1})					
0	0.63	0.62	0.52	0.47	0.49
3	0.63	0.28	0.26	0.15	0.22
6	0.63	0.13	0.11	0.09	0.13
9	0.63	0.10	0.07	0.05	0.06
12	0.63	0.08	0.04	0.04	0.05

Sources: Fageria, N.K. et al., Influence of phosphate rock sources and rates on rice and common bean production in an Oxisol, in *Plant-Soil Interactions at Low pH*, Wright, R.J. et al. (eds.), Kluwer Academic Publisher, Dordrecht, the Netherlands, 539–546, 1991a; Fageria, N.K. et al., Response of upland rice and common bean to liming on an Oxisol, in *Plant-Soil Interactions at Low pH*, Wright, R.J. et al. (eds.), Kluwer Academic Publisher, Dordrecht, the Netherlands, 519–528, 1991b.

[a] Lime was applied about 160 days before sowing the rice crop. First harvest was about 280 days after lime application and second harvest about 1 year after first harvest. Soil samples were taken from 0 to 20 cm soil depth.

To improve liming recommendations, a factor of Al × 2 should be used for species susceptible to soil acidity, Al × 1.5 for moderately tolerant species, and Al × 1 for tolerant species. Lime requirements are expressed in terms of $CaCO_3$ because, for reasons of cost and nutrient value, crushed limestone is the most common product used for neutralizing soil acidity.

Base saturation is another important chemical property of soils, and it is also used as a criterion to make liming recommendations. Base saturation is defied as the proportion of the cation exchange capacity (CEC) occupied by exchangeable bases. It is calculated with the help of the following formula (Fageria, 2006):

$$\text{Base saturation}\,(\%) = \frac{\sum (\text{Ca}, \text{Mg}, \text{K}, \text{Na})}{\text{CEC}} \times 100$$

where CEC is sum of Ca, Mg, K, Na, H, and Al expressed in $cmol_c\ kg^{-1}$.

For routine soil testing in Brazil, Na^+ is generally not determined because of the very low levels of this element in Brazilian Oxisols (Raij, 1991). Hence, Na is not considered in the calculation of CEC or the base saturation. For crop production, soil base saturation levels may be grouped into

TABLE 4.4
Lime Requirement Methods Used by State Soil Testing Laboratories of the United States

State	Method
Alabama	Adams–Evans buffer
Arkansas	Soil pH, exchangeable Ca^{2+}, soil texture, crop
Florida	Adams–Evans buffer
Georgia	Adams–Evans buffer
Kentucky	SMP buffer
Louisiana	$Ca(OH)_2$ titration
Mississippi	Modified Woodruff buffer
North Carolina	Mehlich buffer
Oklahoma	Modified SMP buffer
South Carolina	Adams–Evans buffer
Tennessee	Adams–Evans buffer
Texas	Soil pH, soil texture
Virginia	Soil pH, soil texture

Source: Adapted from Adams, F. (ed.), Crop response to lime in the southern United States, in *Soil Acidity and Liming* (Monograph 12), 2nd edn., American Society of Agronomy, Madison, WI, 211–265, 1984.

TABLE 4.5
Average Recovery Efficiency (%) of Nitrogen for Five Major Cereals in Various Continents

Continent	Millet	Sorghum	Maize	Rice	Wheat
Europe	—	—	40(3)	—	48(34)
Africa	40(25)	45(6)	51(11)	28(30)	39(4)
Asia	40(4)	38(9)	41(12)	39(66)	45(22)
North America	—	18(4)	29(22)	53(1)	51(4)
South America	—	32(9)	32(42)	55(17)	34(32)
Australia	—	35(9)	45(3)	50(9)	43(12)

Sources: Adapted from van Duivenbooden, N. et al., *Fert. Res.*, 44, 37, 1996; Fageria, N.K., *Maximizing Crop Yields*, Marcel Dekker, New York, 1992.

Note: Number of observations between brackets.

very low (less than 25%), low (25%–50%), medium (50%–75%), and high (>75%) (Fageria and Gheyi, 1999). At very low and low base saturation levels, adsorbed hydrogen and aluminum are the predominant cations on the exchange complex. Deficiencies of calcium, magnesium, and potassium are likely to occur in soils with low CEC and very low to low percent base saturation. The following formula is appropriate when base saturation is used to estimate lime requirements (Fageria et al., 1990; Raij, 1991):

$$\text{Lime rate (Mg ha}^{-1}) = \left(\frac{\text{CEC}\,(B_2 - B_1)}{\text{TRNP}} \right) \times \text{df}$$

where
CEC = cation exchange capacity (Ca^{2+}, Mg^{2+}, K^{+}, H^{+} + Al^{3+}) in $cmol_c\ kg^{-1}$
B_2 = desired optimum base saturation
B_1 = existing base saturation
TRNP = total relative neutralizing power of liming material
df = depth factor, 1 for 20 cm depth and 1.5 for 30 cm depth

For Brazilian Oxisols, the desired optimum base saturation for most of the cereals is considered to be in the range of 50%–60%, and for legumes it is considered to be in the range of 60%–70% (Fageria et al., 1990; Fageria, 2009). However, there may be some exceptions. For example, upland rice, which is very tolerant to soil acidity and can produce good yields at base saturations less than 50%.

4.2.3.2 Nitrogen

So far, there is no widely accepted or reliable method that can be used to test soil for available nitrogen. This is because most of the nitrogen in soil is found in organic forms, and its mineralization from this source is dependent on soil and climatic factors that vary constantly during crop growth. Nitrogen mineralization is defined as the conversion of organic N to inorganic N as a result of microbial activity. Nitrogen immobilization is the corollary to mineralization and is defined as the conversion of inorganic N to the organic N form in microbial tissues (Soil Science Society of America, 1997). Nitrogen as NO_3^- is subject to leaching, denitrification, and immobilization by microorganisms, and this further complicates the development of a soil test for available nitrogen (Dahnke and Vasey, 1973).

Due to nitrogen losses by various processes in the soil–plant system, recovery of this nutrient by annual crops is quite low (Table 4.5). The efficiency with which fertilizer N is transferred to grain N in cereals is usually less than 50% and average 33% worldwide (Raun and Johnson, 1999; Johnson and Raun, 2003). This unrecovered N constitutes a potential contributor to groundwater contamination, eutrophication, acid rain, global warming, and farm insolvency. A primary goal of predicting N mineralization from soils and other organic N sources is to increase the overall efficiency of N-use in crop production (Honeycutt, 1994). Various biological and chemical methods have been proposed for estimating the organic N-supplying capacities of soils. A common approach used in the United States is to sample soils to a depth of approximately 0.6 m, preferably in the late winter before planting summer crops. The NO_3^- is extracted from the sample with a neutral salt solution like 1 N KCl, and the amount of NO_3^-–N remaining in the profile is taken into account when making the fertilizer recommendation (Soil Fertility Recommendations for Various Crops and Land Uses Based on Soil Testing Analysis Performed at Texas A&M University Soil, Water and Forage Testing Laboratory). Nevertheless, many soil scientists feel that the transformations and movement of the various forms of soil nitrogen are too complex to warrant their routine use in making fertilizer recommendations (Stanford, 1982; Fageria and Baligar, 2005a; Fageria, 2009). Nitrogen fertilizer recommendations are often made on the basis of long-term crop response data (Cope and Evans, 1985; Fageria, 2009). Accurate recommendations for N fertilizer require knowledge of plant N requirements, external N sources, and N losses from the soil system. These components are represented by the equation (Rice et al., 1995)

$$N_f = N_c - \left(N_{sources} - N_{losses}\right)$$

where
N_f = N fertilizer
N_c = N needed by the crop
$N_{sources}$ = N sources
N_{losses} = N losses

4.2.3.3 Phosphorus

Use of extractant is an important factor in soil test calibration studies for P. Although numerous soil-test methods for estimating extractable P have been developed around the world, their results are difficult to compare because of the very different scale levels used (Zalba and Galantini, 2007). In selecting an extractant for a particular soil and nutrient, the important consideration is the degree of correlation between the extracted nutrient and plant growth. Thomas and Peaslee (1973) have discussed the characteristics of suitable extractors of P. The extractant should

1. Rapidly dissolve and/or desorb soil P and be time independent after 30 min or less.
2. Maintain organic matter and soil clay in a flocculated state.
3. Avoid reprecipitation of dissolved P and/or hydrolysis of organic P.
4. Contain no excess salts, buffers, or ions that interfere with analytical determinations.
5. Extract meaningful quantities of other nutrient ions as well as P.
6. Be easy to prepare, store, and dispose.

There are several solutions used for P extraction from soils (Table 4.6). However, the most common extractants used in routine analysis of P in various parts of the world are Mehlich-1 (0.05 N HCl + 0.025 N H_2SO_4), Bray 1 (0.03 N NH_4F + 0.025 N HCl), and Olsen (0.5 N $NaHCO_3$, pH 8.5). These extractants cover a broad range of soil conditions ranging from acid to alkaline, low to high CEC, and arid to humid (Kleinman et al., 2001).

The Mehlich-1 extractant is suitable for low-CEC, highly weathered, acidic soils. It is a good extractant of calcium phosphates, and extracts some Al–P but not as effectively as Ca–P. In soils where rock phosphate has been applied, care should be taken in using this extractor because it will dissolve some unreacted rock phosphate, resulting in overestimation of the P supply and underestimation of the fertilizer P requirements (Cope and Evans, 1985).

Table 4.7 compares Mehlich-1 and Bray 1 extractants when used to extract P in an Oxisol of central Brazil treated with different P fertilizers. It is clear from this table that, compared to Bray 1, the Mehlich-1 procedure gave higher extractable P values for rock phosphate-treated soil but lower extractable P values when no fertilizer was applied or the soil was treated with a soluble source of P such as triple superphosphate and partially acidulated phosphate rock. These results suggest that the

TABLE 4.6
Reagents Used for Extraction of Available P

Extracting Reagents	Soil/Reagent Ratio	Name of Procedure
0.025 N HCl + 0.03 N NH_4F	1:10	Bray 1
0.1 N HCl + 0.03 N NH_4F	1:17	Bray 2
0.5 M $NaHCO_3$, pH 8.5	1:20	Olsen
0.05 N HCl + 0.025 N H_2SO_4	1:4	Mehlich-1
0.2 N CH_3COOH + 0.2 N NH_4Cl + 0.015 N NH_4F + 0.012 N HCl	1:10	Mehlich-2
0.2 N CH_3COOH + 0.2 N NH_4NO_3 + 0.015 N NH_4F + 0.013 N EDTA	1:10	Mehlich-3
0.002 N H_2SO_4 buffered at pH 3 with $(NH_4)_2SO_4$	1:100	Truog
0.54 N HOAc + 0.7 NaOAc, pH 4.8	1:110	Morgan
0.02 N Ca-lactate + 0.02 N HCl	1:20	Egner
1% citric acid	1:10	Citric acid

Sources: Adapted from Tan, K.H., *Soil Sampling, Preparation, and Analysis*, Marcel Dekker, New York, 1996; Fageria, N.K., *Trop. Agric.*, 66, 249, 1989; Fageria, N.K., *Maximizing Crop Yields*, Marcel Dekker, New York, 1992.

TABLE 4.7
The Effect of P Sources and Rates on P Level (mg kg^{-1}) in the Soil (0–20 cm)

	TSP		APPA		PPPA		PAC		PC		PJ		PPM		PA	
	Bray	Meh.	Bray	Meh.	Bray	Meh.	Bray	Meh.	Bray	Meh.	Bray	Meh.	Bray	Meh.	Bray	Meh.
P Added (kg ha^{-1})	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
First Crop (Rice)																
Control	2.7	1.3	—	—	—	—	—	—	—	—	—	—	—	—	—	—
87	4.1	1.6	5.1	4.9	4.5	5.8	3.5	5.3	3.2	4.5	3.1	3.4	3.1	8.1	3.4	1.6
174	7.9	4.0	7.1	7.3	9.1	21.2	3.8	15.2	3.1	7.5	3.4	7.8	3.6	16.0	3.3	1.8
262	14.1	5.3	11.1	16.3	10.6	25.0	3.9	26.1	3.7	9.9	3.4	9.0	4.0	33.5	4.9	2.4
Linear	**	NS	**	**	**	**	NS	**	NS	NS	NS	*	NS	**	NS	NS
Quadratic	*	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS
Statistical significance																
Sources	**	**														
P rates	**	**														
S × P	**	**														

Sources: Fageria, N.K. et al., Influence of phosphate rock sources and rates on rice and common bean production in an Oxisol, in *Plant-Soil Interactions at Low pH*, Wright, R.J. et al. (eds.), Kluwer Academic Publisher, Dordrecht, the Netherlands, 539–546, 1991a; Fageria, N.K. et al., Response of upland rice and common bean to liming on an Oxisol, in *Plant-Soil Interactions at Low pH*, Wright, R.J. et al. (eds.), Kluwer Academic Publisher, Dordrecht, the Netherlands, 519–528, 1991b.

Notes: TSP, triple superphosphate; APPA, arafertil phosphate partially acidulated; PPPA, phosphate of Patos partially acidulated; PAC, phosphate of Araxa concentrated; PC, phosphate of Catatão; RJ, phosphate of Jacupiranga; PPM, phosphate of Patos de Minas; PA, phosphate of Arbaeti.

*,** Significant at the 5% and 1% probability levels, respectively; NS = nonsignificant.

Mehlich extractant dissolves unreacted phosphate rock and overestimates P availability. Therefore, separate calibration curves are needed for soluble and phosphate rock–based fertilizers.

There are two soil tests that show promise as suitable tests in soils fertilized with soluble as well as phosphate rock–based fertilizers. These are the iron oxide–impregnated paper (P_i) test and the ion exchange resin paper test. In both cases, the strips act as a sink for P mobilized in a soil solution, and the amount of P extracted by the paper depends only on the concentration of P mobilized in the solution, not on the source of P or properties of the soil. Both tests simulate the sorption of P by plant roots without disturbing the chemical equilibrium, unlike other tests that extract P by the destructive dissolution of specific soil P compounds. In both cases, P measured from soils fertilized with phosphate rock–based fertilizers has shown very good correlation with plant response. Field calibration with crops under different pedological and agroecological regimes is needed before using these soil tests in developing fertilizer recommendations (Menon and Chien, 1995; Fageria and Santos, 2008). Similarly, Sahrawat and Sika (2002) reported that establishing the relationship between extractable P in the soil and grain yield and P uptake in long-term field experiments are crucial for evaluating the efficacy of soil tests for determining the P requirements of crops.

The Bray 1 extractant is good for medium- to high-CEC soils, is a strong extractant for Al–P, and extracts some Ca–P due to acid decomposition. This extractant may also dissolve some rock P, and therefore its use on soils where rock phosphate is applied is not recommended. According to Cope and Evans (1985), one possible solution to this problem is to increase the HCl to 0.1 M, as in the Bray 2 extractant, and to do two extractions on the same sample. The Bray 2 extractant has the same concentration of NH_4F (0.03 M) as the Bray 1, but the HCl has been increased to 0.1 M to give it increased capacity to extract less soluble Ca–P.

The Olsen extracting solution (0.5 M $NaHCO_3$, pH 8.5) is normally used for alkaline soils of semiarid regions, which have high CEC and high base saturation and, very often, free $CaCO_3$. Nowadays, some state laboratories in the United States are also using the Mehlich-3 extractant (0.2 N CH_3COOH + 0.25 N NH_4NO_3 + 0.015 N NH_4F + 0.013 N HNO_3 + 0.001 M EDTA) for P extraction (Sims, 1993).

4.2.3.4 Potassium, Calcium, and Magnesium

The commonly used extractants for K, Ca, and Mg are double acid (0.05 M HCl in 0.0125 M H_2SO_4), 1 M NH_4OAc at pH 7, and 1 M NaOAc at pH 4.8. The double-acid extractant is suitable for sandy soils and acid soils with low CEC, whereas ammonium extractants are suitable for a wide range of soils and are most commonly used in routine soil testing laboratories. Detailed descriptions of sample size, volume of extractant, shaking time, and sensitivity are given by Jones (1979). Where the Bray 1 extractant works well for P, it is commonly used to extract K at the same time. In Brazil, 1 M KCl is used to extract Ca and Mg from acid soils in routine soil testing programs.

4.2.3.5 Micronutrients

Use of micronutrients for agronomic and horticultural crops has increased markedly in recent years. Increased use is related to higher nutrient demands from more intensive cropping practices and also from farming marginal lands. Most of the fertilizers used to correct micronutrient deficiencies are water-soluble inorganic sources or soluble organic products such as synthetic chelates or natural organic complexes. These fertilizers may react with soil to decrease their availability to plants. The rates of such chemical reactions may differ considerably with micronutrient fertilizer and soil environment (Mortvedt, 1994). Crop recovery values for micronutrients generally range from only 5% to 10%. Some of the reasons for the low efficiency of micronutrient fertilizers are poor distribution of the low rates applied to soils, fertilizer reactions with soil to form unavailable reaction products, and low mobility to soil, especially of the cationic micronutrients (Cu, Fe, Mn, and Zn).

Various methods have been developed for determining the availability of micronutrients in soils (Cox and Kamprath, 1972). Lindsay and Norvell (1978) developed a diethylenetriaminepentaacetic acid (DTPA) soil test to identify near-neutral and calcareous soils with insufficient available Zn, Fe, Mn,

or Cu for maximum yields of crops. The extractant consists of 0.005 M DTPA, 0.1 M triethanolamine (TEA), and 0.01 M $CaCl_2$ with a pH of 7.3. The soil test consists of shaking 10 g of air-dry soil with 20 ml of extractant for 2 h. The leachate is filtered, and Zn, Fe, Mn, and Cu are measured in the filtrate by atomic absorption spectrophotometry.

The pH of 7.3 buffered with TEA is used to prevent excess dissolution of the trace metals, a process which is highly pH dependent. The presence of 0.01 M $CaCl_2$ enables the extractant to reach equilibrium with CO_2, which minimizes the dissolution of $CaCO_3$ from calcareous soils (Baker and Amacher, 1982). In a preliminary soil test calibration study, Edlin et al. (1983) evaluated four Zn extraction methods (DTPA, EDTA, 1 M NH_4OAc, and 0.1 M HCl) for their ability to separate responding from nonresponding soils in a growth chamber experiment using alfalfa as an indicator plant. The DTPA test (Lindsay and Norvell, 1978) was found to be the most suitable index of Zn-deficient soils, with a critical value of 0.55 mg DTPA-Zn kg^{-1} soil.

Cox and Wear (1977) reported critical Zn soil test levels for corn and rice for three methods (DTPA, 0.1 M HCl, and 0.05 M HCl + 0.0125 M H_2SO_4) based on experiments conducted as a part of a joint regional project that included the southern United States, Pennsylvania, and Puerto Rico. For corn, the critical soil test levels were 0.5 mg Zn kg^{-1} for DTPA, 1.4 mg Zn kg^{-1} for 0.1 M HCl, and 0.8 mg Zn kg^{-1} for the double acid. For rice, the values were 0.7, 1.8, 1.4 mg Zn kg^{-1}, respectively. Similarly, Singh et al. (1987) successfully used DTPA-extractable Zn to predict Zn deficiency in a large number of soil samples taken across Saskatchewan, Canada. In acid soils, the Mehlich-1 (0.05 M HCl + 0.0125 M H_2SO_4) has been satisfactory for Zn and Mn determinations (Cox, 1968; Weaver and Evans, 1968). The DTPA method was developed for use on calcareous soils, but inclusion of soil pH in the interpretation of results makes the method useful for estimating trace metal availability in acid soils well below the pH range for which the test was originally intended (Haq and Miller, 1972). The acid extractants are not recommended for calcareous soils.

For boron, the most satisfactory extractant is hot water. As far as Mo is concerned, water, 1 N NH_4OAc, strong acid, strong base, and ammonium oxalate (pH 3.3) have been investigated to relate extractable soil Mo to plant response. It is reported that many soil factors other than extractable Mo levels affect plant uptake of Mo, so the general usefulness of extractable soil Mo measurements remains quite limited (Cox and Kamprath, 1972; Kubota and Cary, 1982).

Recommended micronutrient rates have been based on results of numerous experiments, and these rates vary with crop, soil, and other factors. The usual application rates (on an elemental basis) range from 1 to 10 kg ha^{-1} for Cu, Fe, Mn, and Zn; <1 kg ha^{-1} for B; and <100 g ha^{-1} for Mo (Reisenauer et al., 1973; Mortvedt, 1994).

4.2.3.6 Aluminum

Aluminum toxicity is one of the most important growth-limiting factors in acid soils in many regions of the world (Fageria et al., 1988). As soil pH drops below 5.0, the chemical stability of Al minerals is reduced and Al is liberated into the soil solution (Lindsay, 1979). Under these conditions, Al toxicity becomes the main factor limiting plant productivity. One of the first visual symptoms of Al toxicity on plants is reduced growth of roots (Fageria, 2009). The toxic effects of Al are more evident in roots than in shoots (Pintro and Taylor, 2004; Moura et al., 2005). Several plant species have developed strategies to avoid Al toxicity (Moura et al., 2005). Proposed Al resistant mechanisms can be classified as internal tolerance and exclusion (Taylor, 1991; Kochian, 1995). The main difference between these mechanisms is the site of Al detoxification: the symplasm (internal tolerance) or apoplasm (exclusion). Internal tolerance mechanisms immobilize, compartmentalize, or detoxify Al in the symplasm (Moura et al., 2005). In contrast, exclusion mechanisms prevent toxic Al from entering the symplasm where sensitive intracellular sites are located (Taylor, 1991). A proposed exclusion mechanism is root excretion of chelating organic substances that form complexes with Al^{3+} ions in the soil solution, which are less phytotoxic than free Al^{+} ions (Hue et al., 1986). Moura et al. (2005) reported that most Al detoxifying

mechanisms in ryegrass were apparently physiological Al-PO_4 precipitation inside the root and chemical $AlSO_4^+$ complex formation in the nutritive solution.

Aluminum ions are most commonly displaced with unbuffered salt solution, such as 1 M KCl, $CaCl_2$, and $BaCl_2$ (Barnhisel and Bertsch, 1982). Extraction techniques employing unbuffered salt solutions are probably best suited for estimating truly exchangeable Al, at least as a first approximation. Other complexing agents and acid salt solutions may extract Al from both exchangeable and nonexchangeable sources, including structural oxyhydroxy polymeric interlayers, organically bound species, and other noncrystalline measurable forms (Barnhisel and Bertsch, 1982).

The species of aluminum ions present are variable with pH. The forms of aluminum include mostly exchangeable Al^{3+} under very acidic conditions (pH < 4.5) and aluminum-hydroxyl ions at higher pH (4.5–6.5) (Carson and Dixon, 1979). In general, the net positive charge of the hydroxyl aluminum species decreases as pH increases and becomes negative in the alkaline pH range. Aluminum ions generate hydrogen ions through a series of hydrolysis reactions shown below (Lindsay, 1979):

$$Al^{3+} + 2H_2O \leftrightarrow Al(OH)_2^+ + 2H^+$$

$$Al^{3+} + 3H_2O \leftrightarrow Al(OH)_3^0 + 3H^+$$

$$Al^{3+} + 4H_2O \leftrightarrow Al(OH)_4^- + 4H^+$$

$$Al^{3+} + 5H_2O \leftrightarrow Al(OH)_5^{2-} + 5H^+$$

$$2Al^{3+} + 2H_2O \leftrightarrow Al_2(OH)_2^{4+} + 2H^+$$

Exchangeable Al^{3+} precipitates as insoluble Al hydroxyl species as pH increases, and is reported to decrease 1000-fold for each unit increase in pH (Lindsay, 1979). However, at pH values greater than 6.5, Al becomes increasingly soluble as negatively charged aluminates form (Haynes, 1984). $Al(OH)^{2+}$ is of minor importance and exists over only a narrow pH range. $Al(OH)_5^{2-}$ occurs at pH values above those usually found in soils. The Al^{3+} ion is predominant below pH 4.7, $Al(OH)_2^+$ between pH 4.7 and pH 6.5, $Al(OH)_3^0$ between pH 6.5 and pH 8.0 and $Al(OH)_4^-$ above pH 8 (Bohn et al., 1979; Fageria and Baligar, 2008).

4.2.4 Calibration and Interpretation

Soil test values have no meaning if they are not calibrated against crop response for appropriate interpretation and fertilizer recommendations (Fageria and Santos, 2008). After a soil test procedure has been selected on the basis of thorough greenhouse and laboratory experimentation, it is necessary to calibrate the test on a large number of sites under field conditions. Calibration should be done for each crop and each agroclimatic region of interest. The objective of soil calibration is to determine the amount of nutrient that must be added to a specific soil at each soil test level of that nutrient to obtain maximum yield. In soil test calibration studies, the following are important considerations:

1. Soils should be deficient in the nutrient for which the calibration study is conducted.
2. All other nutrients except the one under study should be applied in adequate amounts.
3. Other factors that affect growth, such as water deficiency, diseases, insects, and weeds, should not be limiting or their presence should be properly documented.

4. It is more desirable to have a large number of experiments at different locations than to have more replications at a few sites.
5. Under field conditions, all soil and climatic variables cannot be controlled effectively. It is necessary to repeat field calibration studies for 3–5 years before definitive conclusions can be made.
6. Nutrient levels selected for calibration studies should cover a wide range from deficiency to sufficiency.

For interpretation of soil test results, crop yields are plotted against soil test values. Absolute yield values should be transformed into relative yield values by the following formula:

$$\text{Relative yield}\,(\%) = \frac{\text{Yield of control or treated plot}}{\text{Maximum yield of treated plot}} \times 100$$

According to Evans (1987), a wide scattering of absolute yields may occur as a result of factors other than soil fertility. This scattering of absolute yields does not necessarily mean that there is poor correlation, but a better relationship may be obtained by using a relative yield to eliminate some of the climate and site influences.

The use of soil analysis as a fertilizer recommendation method is based on the existence of a functional relationship between the amount of nutrient extracted from the soil by chemical methods and the crop yield. When a soil analysis test shows a low level of a particular nutrient in a given soil, application of that nutrient is expected to increase crop yield. Figure 4.3 shows a theoretical relationship between nutrient applied and relative crop yield. Nutrient analysis has been arbitrarily classified as very low, low adequate, high, and excess. Under the very low nutrient level, relative crop yield is expected to be less than 50%, and a larger application of fertilizer for soil-building purposes is required. After the application of the nutrient, growth response is expected to be dramatic and profitable. Under the low fertility level, relative yield is expected to be 50%–75%. Under this situation, annual application of fertilizer is necessary to produce maximum response and increase soil fertility. The increased yield usually justifies the cost of fertilization. When a soil analysis test shows an adequate level, relative crop yield is expected to be 75%–100%. Normal annual applications to produce maximum yields are recommended. In this case, more fertilizer may increase yields

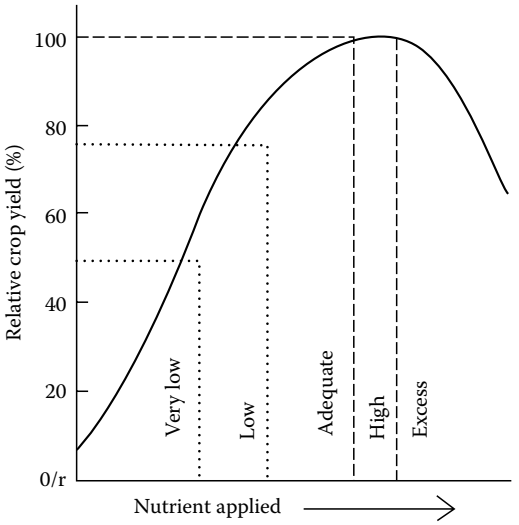

FIGURE 4.3 Theoretical relationship between nutrient applied and relative yield.

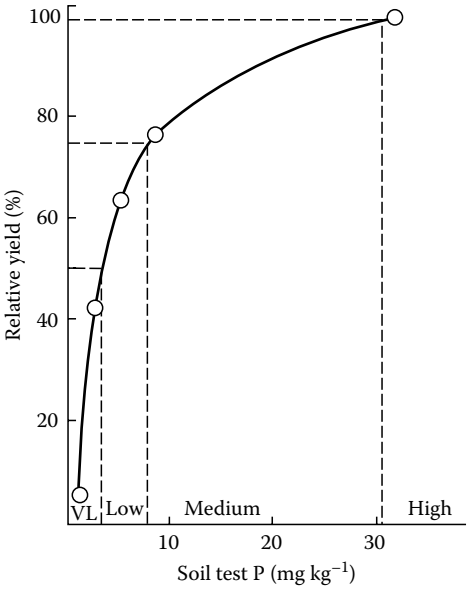

FIGURE 4.4 Relationship between soil test P and relative yield of common bean.

slightly, but the added yield may not pay back the expense of the additional fertilizer. Under the high nutrient level, there is no increase in yield. Under this situation, a small application is necessary in order to maintain the soil level. The amount suggested may be doubled and applied in alternate years. When the soil test shows very high or excess levels of a nutrient, the yield may be reduced due to toxicity or imbalances of nutrients. Under this situation, there is no need to apply a nutrient until the level drops back into the low range. To get such nutrient level and yield relationship, it is necessary to conduct fertilizer yield trials in several locations in a given agroecological region for different crops. Figure 4.4 shows the relationship between soil test P and relative yield of common bean (*Phaseolus vulgaris* L.) in an Oxisol of central Brazil.

In calibration studies, the CEC of soil plays an important role. Soils with high CEC release less P to chemical extractants at comparable levels of adequacy than do the lower-CEC soils, and these should therefore be classified differently for making P fertilizer recommendations (Cope, 1981). The reverse is true for K, Ca, and Mg (Cope and Evans, 1985).

4.2.5 Fertilizer Recommendations

The last phase in soil testing is making fertilizer recommendations. After calibration and interpretation, soil test data need to be associated with appropriate fertilizer rates. Each of the four common interpretative categories (very low, low, medium, and high) signifies different fertilizer rates. The very low level requires large amounts of fertilizer, the low level needs annual application, the medium level requires normal application, and the high level needs little or no fertilizer. The economic loss to farmers is not as great with excess fertilization as with underfertilization by the same proportion. Thus, it would seem more profitable to be sure that the optimum amount is recommended even if there is a chance that the rate would be more than optimum, as in unfavorable growth years (Barber, 1973). This holds especially true for nutrients not easily leached from the soil.

In making fertilizer recommendations, not only the soil test but also climate, disease, insects, previous crops, previous fertilizer application, and soil yield potential should be considered. Maximum crop yield is obtained by fertilizer application only if all growth factors are at optimum levels. Besides optimum fertilizer application, other cultural practices such as timely planting, adequate plant density, effective fertilizer application, and efficient harvesting also contribute to

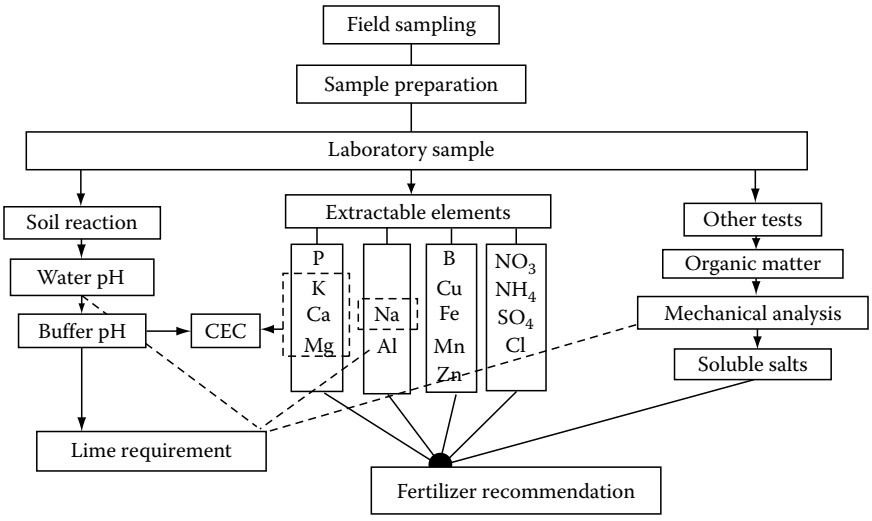

FIGURE 4.5 Sequence for conducting a soil test, from field sampling through laboratory analysis to lime and fertilizer recommendations. (From Jones, J.B., Jr., Soil testing and plant analysis: Procedures and use, Technical Bulletin 109, Food and Fertilizer Technological Center, Taipei City, Taiwan, 14 p, 1988.)

increased yield. If a nutrient is mobile, as nitrogen is, large amounts will be needed as potential yield increases. Figure 4.5 shows a sequence for soil testing through fertilizer recommendations.

4.3 PLANT ANALYSIS

Plant analysis in a narrow sense is the determination of the concentration of an element or extractable fraction of an element in a sample taken from a particular part or portion of a crop at a certain time or stage of morphological development (Munson and Nelson, 1973). The concentration is generally expressed on a dry weight basis. Plant analysis considerations include collection of the plant samples, preparation of the samples for analysis, interpretation of analytical results, and recommendations. Plant analysis has many applications, such as (1) diagnosis of nutrient deficiencies, toxicities, or imbalances; (2) measurement of the quantity of nutrients removed by a crop to replace them in order to maintain soil fertility; (3) estimating overall nutritional status of the region or soil types; (4) monitoring of the effectiveness of the fertilizer practices adopted; (5) prediction of crop yields; and (6) estimation of nutrient levels in diets available to livestock (Smith, 1986). With the development of instruments such as atomic absorption spectrophotometers, spark emission spectrometers, and inductively coupled plasma (ICP) emission spectrometers, plant analysis has become more sensitive and simplified.

After identifying a nutrient deficiency in a growing crop through plant analysis, its correction depends on the nutrient and growth stage of the crop. If the deficiency is identified in an early growth stage and the nutrient is a micronutrient, it is easy to correct, and the farmer may get a favorable return on his investment. The most common method of correcting nutrient deficiencies in a growing crop is foliar application of the deficient nutrient. For field crops, major nutrients should not be applied by foliar application. To satisfy plant requirements for major nutrients, several foliar applications are necessary for beneficial results, and this is rarely economically feasible.

4.3.1 Collecting the Plant Sample

Probably no other single aspect of the plant analysis technique can have as much effect on the final result as the procedure used to collect the sample for analysis (Jones, 1985). The primary

TABLE 4.8
Plant Parts and Number of Plants to Be Sampled for Field Crops at Different Growth Stages

Crop	Growth Stage	Plant Part to Sample	No. of Plants to Sample
Wheat	Seedling stage	All the aboveground portion	50–100
Rice, barley	Prior to heading	The four uppermost leaves	50–100
Corn	Seedling stage	All the aboveground portion	20–30
	Prior to tasseling	The entire leaf fully developed below the whorl	15–25
	From tasseling and shooting to silking	The entire leaf at the ear node or immediately below or above it	15–25
Soybean or other beans	Seedling stage	All the aboveground portion	20–30
	Prior to or during initial flowering	Two or three fully developed leaves at the top of the plant	20–30
Sugar beets	Midseason	Fully extended and mature leaves midway between the younger center leaves and the oldest leaf whorl on the outside	30–40
Peanuts	Prior to or at bloom stage	Mature leaves from the main stems and either cotyledon lateral branch	40–50
Cotton	Prior to or at bloom or when first squares appear	Youngest fully mature leaves on main stem	30–40
Alfalfa	Prior to or one-tenth bloom stage	Mature leaf blades taken about one third of the way down the plant	40–50
Clover	Prior to bloom	Mature leaf blades taken about one third of the way down from the top of the plant	40–50
Sugarcane	Up to 4 months	Third or fourth fully developed leaf from top	15–25
Sorghum	Prior to or at heading	Second leaf from top of plant	15–25

Source: Compiled from Gorsuch, T.T., Dissolution of organic matter, in *Accuracy in Trace Analysis: Sampling, Sample Handling, Analysis*, Vol. 1, Special Publication 422, Lafleur, P.D. (ed.), National Bureau of Standards, Washington, DC, 491–508, 1976.

consideration in deciding what part of the plant to sample is the degree to which nutrient concentrations in a given part reflect the nutrient status of the entire plant. In particular, it is important to use a plant part that gives a sharp transition from a concentration that reflects a deficiency of the nutrient to one that indicates an adequate supply of the nutrient (Ulrich et al., 1959). Jones et al. (1971) and Jones and Steyn (1973) proposed a scheme indicating which plant parts should be sampled at different growth stages. This scheme for important field crops is presented in Table 4.8. When sampling, precautions should be taken to avoid soiled, diseased, and insect-damaged or mechanically damaged plants and to exclude dying or dead tissue. Plant samples should be collected in paper bags rather than plastic bags.

4.3.2 Sample Preparation

After collecting plant tissues, the next step is preparation of the sample, which may include washing, drying, grinding, and storage. Plant material should be transported from the field to the analytical laboratory as quickly as possible to avoid respiratory and evaporation losses in weight and enzymatic activity, both of which produce corresponding errors in nutrient determination (Reuter et al., 1986). The plant material destined for micronutrient analysis should then be washed in deionized water

to remove deposits from dust, pesticide, or nutrient foliar sprays. If deposits cannot be removed by deionized water, a 0.1%–0.3% detergent solution can be used. If samples cannot be washed immediately, material should be stored in a refrigerator at 5°C to minimize respiratory losses and plant spoilage. After washing, the samples can be dried to a constant weight in a forced-draft oven at 70°C–75°C. Prolonged drying at temperatures in excess of 80°C can promote thermal decomposition and appreciable loss of volatile constituents (Grundon and Asher, 1981). Dried material can be ground to manageable sizes and mixed to provide homogeneous samples for chemical analysis. However, grinding is not essential for small-sized samples because the whole sample can be crushed by hand and weighed for analysis (Reuter et al., 1986). Grinding should be performed in mills having stainless grinding surfaces to minimize contamination. Ground material can be stored in glass or polycarbonate containers under cool, dry, or refrigerated conditions for future analysis. Stored samples should be redried for about 8–12 h just prior to weighing for analysis if the relative humidity in the laboratory is high.

4.3.3 Chemical Analysis

It is not the purpose of this chapter to give detailed analytical procedures for tissue analysis. These procedures are available in several publications (e.g., Ramirez-Munoz, 1968; Norrish and Hutton, 1977; Liegel et al., 1980; Jones, 1981, 1985; Munter et al., 1984). However, a brief discussion of digestion methods is appropriate. There are two common digestion methods called dry ashing and wet oxidation. Both of these methods have advantages and disadvantages. A comparison of these two methods is given in Table 4.9. The basic digestion reagents used in wet oxidation are (1) nitric and sulfuric acids, (2) sulfuric acid and hydrogen peroxide, and (3) mixtures containing perchloric acid (Jones, 1985). Among these, nitric and sulfuric acid digestion is suitable for a wide range of sample types. Problems may occur with samples high in Ca when calcium sulfate precipitation causes losses due to coprecipitation. Sulfuric acid and hydrogen peroxide digestion is a vigorous procedure with potential for losses of some elements in the presence of chlorides. A mixture of nitric (sometimes sulfuric) and perchloric acids is a widely used digestion reagent, although its use requires extreme care and a specially designed hood (Jones, 1985). Tolg (1974) has given characteristics of common wet oxidation procedures, which are presented in Table 4.10. It is now a common practice to use block digestors in wet oxidation processes so that temperature can be regulated and thereby avoid losses due to rapid boiling and excessive temperatures.

In the dry ashing oxidation procedure, care should be taken regarding the vessels used and temperature. Silica (quartz) is probably one of the best materials for the ashing vessel, although

TABLE 4.9
Comparison of Dry and Wet Oxidation Methods Used for Plant Digestion

Dry Ashing	Wet Oxidation
Time consuming	Comparatively rapid
Requires higher temperature, and chances of nutrient loss by volatilization	Low temperature and volatilization losses are less
Generally more sensitive to nature of sample	Generally less sensitive to nature of sample
Requires less supervision	Requires more supervision
Reagent blank smaller	Reagent blank larger
Can handle large samples	Difficult to handle large samples

Source: Compiled from Gorsuch, T.T., Dissolution of organic matter, in *Accuracy in Trace Analysis: Sampling, Sample Handling, Analysis*, Vol. 1, Special Publication 422, Lafleur, P.D. (ed.), National Bureau of Standards, Washington, DC, 491–508, 1976.

TABLE 4.10
Wet Oxidation Digestion Reagents and Their Applicability

Reagents	Applicability to Organic Matrix	Remarks
H_2SO_4/HNO_3	Vegetable origin	Most commonly used
H_2SO_4/H_2O_2	Vegetable origin	Not very common
HNO_3	Biological origin	Easily purified reagent, short digestion time, temperature 350°C
$H_2SO_4/HClO_4$	Biological origin	Suitable only for small samples; danger of explosion
$HNO_3/HClO_4$	Protein, carbohydrate (no fat)	Less explosive
$H_2SO_4/HCO_3/HClO_4$	Universal (also fat and carbon black)	No danger with exact temperature control

Source: Adapted from Tolg, G., The basis of trace analysis, in *Methodicium Chimicum, Vol. 1, Analytical Method, Part B, Micromethods, Biological Methods, Quality Control, Automation*, Korte, F. (ed.), Academic Press, New York, 698–710, 1974.

well-glazed, acid-washed porcelain high-form crucibles are equally suitable vessels for most uses (Jones, 1985). Ashing temperature should not exceed 500°C to avoid volatilization losses for most elements.

Besides appropriate oxidation procedures, some other precautions are necessary to achieve accuracy and precision in plant chemical analysis. These precautions include checking the purity of the reagents by including blanks in routine testing, use of appropriate methods to account for known interferences, inclusion of reference plant material with each batch of samples to monitor analytical performance, regularly checking the authenticity of standard solutions used for establishing calibration curves and replacing them at defined intervals, and exchanging samples with other laboratories on a regular basis as a means of verification of analytical procedures (Reuter et al., 1986).

Since 1956, the Department of Soil Science, University of Wageningen, the Netherlands, has been comparing chemical analytical results from laboratories all over the world (Houba et al., 1986). Houba and coworkers compared the analytical results of 23 elements, using data from the collaborative interlaboratory study (Table 4.11). In particular, the relationship between content level and coefficient of variation (CV) was examined. Usually, a constant CV was found at high content levels, with a sharp increase in CV at low levels. The precision found for N, P, K, Ca, Mg, Zn, and nitrate was high enough (CV < 20%) to yield reasonably comparable content values. Comparison of analytical results for B, Cu, Fe, Cd, Mn, and Na may be difficult, since about 20% CV was reached at the levels usually present in plant material. The analytical results for Al, Co, Cr, Mo, Ni, Pb, S, Se, and sulfate varied considerably, irrespective of the content level, which means that results are very difficult to reproduce with these elements.

The data presented by Houba et al. (1986) can be used to assess the possibilities and limitations of plant analysis for the evaluation of the nutrient status of plants (Table 4.11). No analytical problems are to be expected with the determination of N, P, and K, since the normal levels are much higher than the values that correspond to 20% CV, a maximum acceptable value chosen by these authors. From Table 4.11 it is apparent that the situation for Ca, Cl, Mg, and Zn is also favorable. Comparison of results is difficult for B, Cu, Fe, and Mn, since values that correspond with 20% CV fall in the range of normal values. Elements like Al, Co, Cr, Mo, Ni, Pb, S, Se, and sulfate pose problems with respect to the comparability of analytical results from different laboratories. These results suggest that for many elements plant analysis techniques still need to be refined.

TABLE 4.11
Lowest Measurable Level of Some Nutrients for a Chosen Interlaboratory Variability Level of 20% CV Compared to Normal Nutrient Values in the Literature[a]

Nutrient	Lowest Measurable Concentration	Normal Concentration
NO_3	15	—
Ca	30	188–338
Mg	15	80–180
Na	30	—
Cl	40	60–600
B	10	9–75
Cu	7.5	4–17
Fe	200	50–200
Mn	25	30–200
Zn	15	22–100

Sources: Lowest measurable concentration: Houba, V.J. et al., *Neth. J. Agric. Sci*., 34, 449, 1986; normal concentration—Average values of Finck, A., *Dung. Bodenk*., 119, 197, 1968; Jones, J.B., Jr., Plant tissue analysis for micro-nutrients, in *Micronutrients in Agriculture*, Mortvedt, J.J. et al. (eds.), Soil Science Society of America, Madison, WI, 319–347, 1972; Mengel, K. and Kirkby, E.A., *Principles of Plant Nutrition*, 3rd edn., International Potash Institute, Bern, Germany, 1982.

[a] Values of NO_3, Ca, Mg, Na, and Cl are in mmol kg^{-1} and values of B, Cu, Fe, Mn, and Zn are in mg kg^{-1}.

4.3.4 Interpretation

The basis for plant analysis as a diagnostic technique is the relationship between nutrient concentration in the plant and growth and production response. This relation should be significant to have complete interpretation in terms of deficient, adequate, and excess nutrient concentrations in the plant. Curves representing the relationship between nutrient concentration and growth response vary in shape and character depending on both the nutrient concentration in the growth medium and the plant species. A hypothetical curve showing this relationship is shown in Figure 4.6. In the literature, several different terminologies have been used in classifying nutrient concentrations in plant tissue. On the basis of Figure 4.6, nutrient concentrations can be classified as deficient, marginal, excess, and toxic. When nutrients are in the deficiency range, plant growth and yield are significantly reduced and foliar deficiency symptoms appear. In this range, application of the nutrient results in a sharp increase in growth with very little change in nutrient concentration in the plant. In the marginal range, growth or yield is reduced, but plants do not show deficiency symptoms, and both nutrient concentrations and growth increase as more nutrient is absorbed. Sometimes the marginal range is also called the transition zone (Ulrich and Hills, 1973). Within the marginal or transition zone lies the critical level or concentration. The critical level can be defined as that concentration at which the growth or yield begins to decline significantly. This, of course, is a matter of judgment and how one interprets the term (Munson and Nelson, 1973). However, under most practical farming conditions, a decrease of 20% from optimum yield can be considered as a significant decrease in crop yield. This is an arbitrary value based on practical experience of the authors. The critical value is normally estimated on the basis of a 5%, 10%, or 20% reduction in maximum yield (Ulrich and Hills, 1973; Reuter and Robinson, 1986; Fageria, 1987). In determining critical nutrient concentrations experimentally,

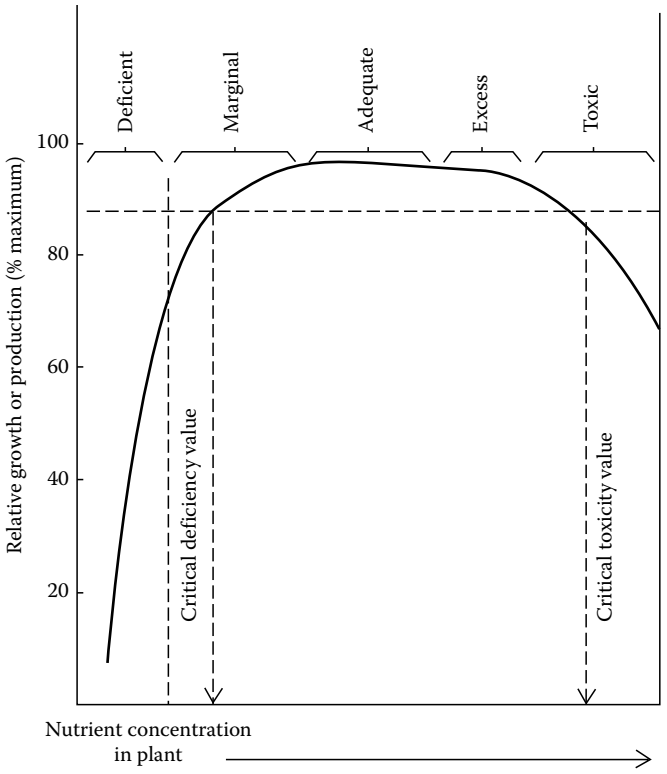

FIGURE 4.6 Relationship between yield and nutrient concentration in plant. (Adapted from Fageria, N.K., *Commun. Soil Sci. Plant Anal*., 35, 961, 2004.)

it is important that plant growth not be limited by factors other than supply of the nutrient being studied. The third range or zone is the adequate zone, in which there is no increase in growth but nutrient concentration increases. This classification is also known as satisfactory, normal, or sufficient concentration. The high classification range represents the range of concentrations between the adequate and toxic ranges. Fertilizer use on crops with values in this range should be reduced until the nutritional status of plants lies in the adequate range (Reuter and Robinson, 1986). The toxic range is the range of nutrients in which there is reduction in growth and yield but concentration of nutrients continues to increase. In this range plants start showing toxicity symptoms. The critical toxicity value lies in this range (Figure 4.6). Table 4.12 shows average adequate concentrations for essential nutrients in crop plants. No doubt these values vary with soil, climate, crop, and management practices, and it is very difficult to make generalizations. Generalized values do give the reader some idea about what adequate levels of nutrients are in crop plants. Specific values for the adequacy range are presented in chapters devoted to individual crops. Figure 4.7 shows the various steps from plant sampling through interpretation of analysis results and recommendations.

4.3.5 Factors Affecting Nutrient Concentrations

Nutrient concentrations in plants are affected by several factors, including species, cultivar, plant age, interaction with other nutrients, and environmental factors such as moisture supply, humidity, and light. A brief discussion of these factors is given in this section.

TABLE 4.12
Average Concentration of Essential Nutrients in Dry Matter Sufficient for Adequate Growth of Field Crops[a]

Nutrient	g kg^{-1} or mg kg^{-1}	μmol g^{-1}
Carbon	450	37,500
Oxygen	450	38,125
Hydrogen	60	60,000
Nitrogen	12	1,000
Phosphorus	1.9	60
Potassium	9.8	250
Calcium	5.0	125
Magnesium	1.9	80
Sulfur	1.0	30
Iron	112	2
Manganese	55	1
Zinc	20	0.3
Copper	6	0.1
Boron	22	2
Molybdenum	0.1	0.001
Chlorine	106	3

Sources: Bergmann, W. and Neubert, P., *Plant Diagnosis and Plant Analysis*, Vebgustav Fischer Verlag, Jena, Germany, 1976; Salisbury, F.B. and Ross, C.W. (eds.), Mineral nutrition, *Plant Physiology*, 3rd edn., Wadsworth, Belmont, CA, 96–113, 1985.

[a] Values of macronutrients are in g kg^{-1} and values of micronutrients in mg kg^{-1}.

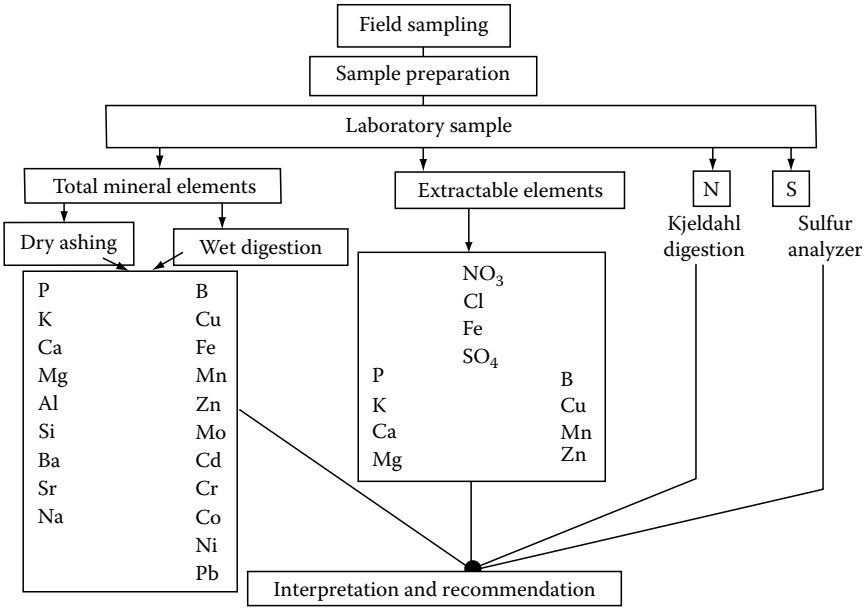

FIGURE 4.7 Sequence for conducting a plant analysis, from field sampling through laboratory analysis to interpretation and recommendations. (From Jones, J.B., Jr., Soil testing and plant analysis: Procedures and use, Technical Bulletin 109, Food and Fertilizer Technological Center, Taipei City, Taiwan, 14 p, 1988.)

4.3.5.1 Genotypic Differences

Differences in nutrient absorption and utilization among field crops and cultivars within a crop are well established (Lafever, 1981; Vose, 1984; Baligar et al., 1987, 2001; Gerloff, 1987; Itamar et al., 1987; Saric, 1987; Siddiqui et al., 1987). Nutrient concentration and uptake by different plant genotypes are the most important criteria used in recent years for identifying the existing genetic specificity of plant mineral nutrition (Saric, 1987). Nutrient uptake values are transformed into a nutrient use efficiency ratio, and this ratio is one of the best parameters for comparing the different plant species or cultivars in terms of nutrient utilization (Gerloff and Gabelman, 1983). The nutrient efficiency ratio is the milligrams of dry matter produced per milligram of element absorbed by a plant or present in a plant part. The ratio should be compared under stress and adequate nutrient supply to verify plant species or cultivar differences in nutrient utilization under suboptimum and optimum conditions.

TABLE 4.13
Soil and Plant Mechanisms and Processes and Other Factors That Influence the Genotypic Differences in Nutrient Efficiency in Plants at Nutrient Stress Conditions

A. Nutrient acquisition
   1. Diffusion and mass flow (buffer capacity, ionic concentration, ionic properties, tortuosity, soil moisture, bulk density, temperature)
   2. Root morphological factors (number, length, root hair density, root extension, root density)
   3. Physiological (root:shoot, root microorganisms such as vesicular arbuscular mycorrhiza (VAM) fungi, nutrient status, water uptake, nutrient influx and efflux, rate of nutrient transport in root and shoot, affinity to uptake Km, threshold concentration C_{min})
   4. Biochemical (enzyme secretion as phosphatase, chelating compounds, siderophore), proton exudate, organic acid such as citric, trans-aconite, melic acid exudate

B. Nutrient movement in root
   1. Transfer across endodermis and transport within root
   2. Compartmentalization/binding within roots
   3. Rate of nutrient release to xylem

C. Nutrient accumulation and remobilization in shoot
   1. Demand at cellular level and storage in vacuoles
   2. Retransport from older to younger leaves and from vegetative to reproductive parts
   3. Rate of chelates in xylem transport

D. Nutrient utilization and growth
   1. Metabolism at reduced tissue concentration of nutrient
   2. Lower element concentration in supporting structure, particularly the stem
   3. Elemental substitution, e.g., Na for K function
   4. Biochemical (nitrate reductase for N-use efficiency, glutamate dehydrogenase for N metabolism, peroxidase for Fe efficiency, pyruvate kinase for K deficiency, metallothionein for metal toxicities)

E. Other factors
   1. Soil factors
      a. Soil solution (ionic equilibria, solubility precipitation, competing ions, organic ions, pH, phytotoxic ions)
      b. Physicochemical properties of soil (organic matter, pH, aeration, structure, soil moisture)
   2. Environmental effects
      a. Intensity and quality of light (solar radiation)
      b. Temperature
      c. Moisture (rainfall, humidity)
   3. Plant diseases, insects, and allelopathy

Source: Compiled from Baligar, V.C. and Fageria, N.K., Nutrient use efficiency in acid soils: Nutrient management and plant use efficiency, in *Paper Presented at 4th International Symposium on Plant-Soil Interactions at Low pH*, Belo Horizonte, Brazil, March 17–24, 1996.

Table 4.13 summarizes various soil and plant mechanisms and processes and other factors that influence genotypic differences in plant processes and other factors that influence genotypic differences in plant nutrient efficiency. Similarly, a summary of morphological and physiological traits in plants associated with major nutrient use efficiency is presented in Table 4.14. A detailed description of this subject can be found in Fageria and Baligar (1993), Baligar and Fageria (1996), and Fageria (2009).

TABLE 4.14
Efficiency Traits and External Factors That Determine Nutrient Efficiency in Plants

Morphological and Physiological Traits	External Factors That Improve Efficiency
Nitrogen	
• Root length density, ratio of lateral/primary roots • Higher efficiency for uptake, incorporation, utilization • Higher dry matter production/unit N; harvest index (H), nutrient harvest index (NHI) • Higher physiological efficiency index for N (PEN = kg grain produced/kg N absorbed) • Nitrate reductase levels (uptake) • Glutamate dehydrogenase (metabolism) • Arginine residue (uptake/transport) • NO_3/NH_4 nutrition	• Use high-yielding, N-efficient cultivars • Fertilizers—right level, time, and depth of placement • Suitable N source use of ammonification/nitrification inhibitors • Incorporate crop residue • Reduce leaching, denitrification, volatilization losses • Maintain adequate moisture and other essential nutrients • Control weeds, insects, and diseases
Phosphorus	
• Root—fibrous roots, high root density • High density and length of root • Hair • Exudates—piscidic acid • High acquisition capacity • More dry matter/unit P absorbed • Partitioning organic/inorganic P • High levels of sucrose to glucose, fructose, and phosphatase enzyme • High phytic phosphate in grain	• Use of P-efficient cultivars • Use of phosphate rock and inorganic forms • Fertilizer band/strip placement • Incorporation of organic matter • Lime addition • Adequate supply of moisture and other nutrients • VAM-increased root surface • Control of weeds, diseases, and insects
Potassium	
• High efficiency (uptake, incorporation, utilization) • High dry matter/unit K absorbed • K uptake and transport • Pyruvate kinase (low K status) • Membrane mechanisms	• Use of K-efficient cultivars • Topdress—light-textured soil • Incorporate crop residue • Control of weeds, diseases, insects • Addition of other nutrients (NP) • Reduce leaching and run-off losses
Calcium/Magnesium	
• High dry matter/unit of nutrient • High efficiency (uptake, incorporation, utilization)	• High-yielding crops • Adequate levels of moisture and other nutrients • Type and quality of liming materials and incorporation • Control of weeds, diseases, and insects

Source: Compiled from Baligar, V.C. and Fageria, N.K., Nutrient use efficiency in acid soils: Nutrient management and plant use efficiency, in *Paper Presented at 4th International Symposium on Plant-Soil Interactions at Low pH*, Belo Horizonte, Brazil, March 17–24, 1996.

4.3.5.2 Plant Age

Growth and development of a plant make a difference in nutrient concentration in plant organs. Normally, as a plant ages, nutrient concentrations expressed per unit dry weight decrease. This is viewed as a dilution effect (Jarrell and Beverly, 1981). A relationship between dry matter yield of shoots or grain and N concentration in the shoot or grain of lowland rice at different growth stages is shown in Table 4.15. Based on this relationship, optimum N concentrations in shoots at different growth stages and in the grain at harvest were determined. Optimum N concentrations in shoots varied from 43.4 g kg^{-1} at initiation of tillering to 6.5 g kg^{-1} at physiological maturity. The N concentration in the grain at physiological maturity was 11 g kg^{-1}. Hence, optimal N concentration in shoots of rice decreased with advanced plant age. During grain filling, N content of non-grain tissue generally decreases while grain N content increases (Bauer et al., 1987; Wilhelm et al., 2002). However, shoot leaf and stem dry weight increased with age up to flowering and then decreased (Fageria, 2003). Decreases in leaf and stem dry weight after flowering was related to translocation of assimilate from the leaves and stem to the panicle from flowering to maturity (Black and Siddoway, 1977; Fageria, 2009). In rice, 60%–90% of the total C accumulated in panicles at the time of harvest was derived from photosynthetic after heading, and the flag leaves are the organs that contribute most to grain filling (Yoshida, 1981).

Concentrations of N in most tissues of crop plants decreased with increasing plant age (Figure 4.8). This was as expected because with increasing plant age, more dry matter was produced, diluting the concentration of nutrients accumulated (Fageria, 2009). Data in Figure 4.9 show that the P concentration in the shoot of upland rice, dry bean, corn, and soybean decreased with increasing plant age. Maier et al. (2002) reported that mobile nutrients such as N, P, and K usually show a decline in concentration with the advancement of plant age. In contrast, nutrients of low or intermediate mobility, for example, Ca, B, Fe, and Mn, tend to show an increase in age in potato.

4.3.5.3 Nutrient Interactions

Interactions between nutrients in crop plants occur when the supply of one nutrient affects the absorption and utilization of other nutrients. This type of interaction is most common when one nutrient is in excess concentration in the growth medium. Nutrient interactions can occur at the root surface or

TABLE 4.15
Relationship between Dry Matter Yield of Shoot or Grain (Y) and N Concentration in Shoot or Grain at Different Growth Stages in Lowland Rice

Plant Growth Stage	Regression	R^2	Optimum N Concentration for Maximum Shoot or Grain Yield (g kg^{-1})
IT (22)[a]	$Y = -439.4654 + 22.5403X - 0.0946X^2$	0.39[NS]	43.4
AT (35)	$Y = -8974.3480 + 586.9736X - 8.4265X^2$	0.74*	34.6
IP (71)[a]	$Y = 211.7915 - 34.9390X + 28.1748X^2$	0.88**	12.7
B (97)	$Y = -36286.13 + 7325.2430X - 285.4674X^2$	0.77*	12.8
F (112)	$Y = -44383.16 + 10690.71X - 485.6974X^2$	0.94**	11.0
PM (140)	$Y = -100159.00 + 33792.63X - 2605.362X^2$	0.94**	6.5
PM (140)[b]	$Y = 1141085.70 + 27046.20X - 1237.72X^2$	0.78*	10.9

Source: Adapted from Fageria, N.K., *Commun. Soil Sci. Plant Anal.*, 34, 259, 2003.

Notes: Values are averages of 3 years field experimentation. IT, initiation of tillering; AT, active tillering; IP, initiation of panicle; B, booting; F, flowering; PM, physiological maturity. Values in the parentheses represent age of the plants in days after sowing.

[a] Where regression equation was nonsignificant or regression coefficient was negative, average value across the N rates was considered as adequate N concentration for maximum yield.

[b] In this line, values are for grain yield.

*,** Significant at the 5% and 1% probability level, respectively; NS, nonsignificant.

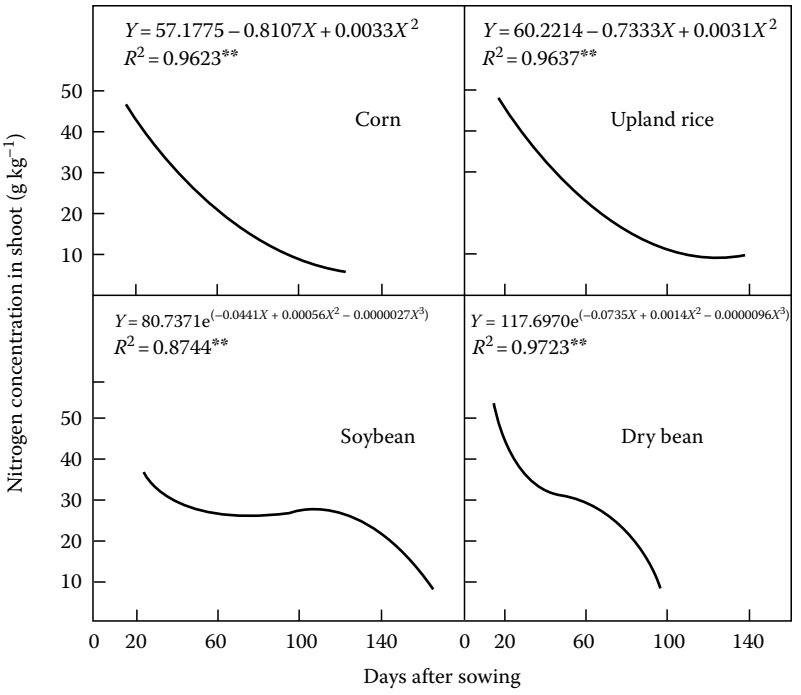

FIGURE 4.8 Relationship between N concentration in shoot of corn, upland rice, soybean, and dry bean as a function of plant age.

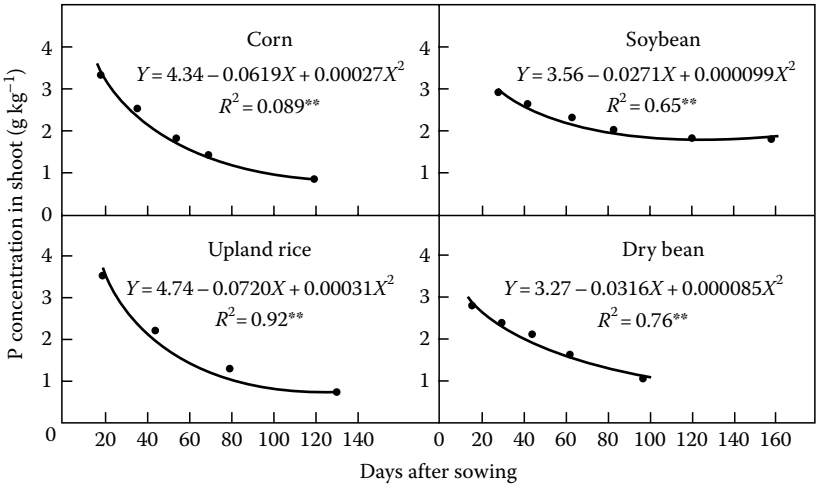

FIGURE 4.9 Relationship between P concentration in shoot of corn, upland rice, soybean, and dry bean as a function of plant age. (Adapted from Fageria, N.K., *Commun. Soil Sci. Plant. Anal.*, 35, 961, 2004).

within the plant. According to Robson and Pitman (1983), nutrient interactions can be classified into two major categories. In the first category are interactions that occur between ions because the ions are able to form a chemical bond. Interactions in this case are due to formation of precipitates or complexes. For example, this type of interaction occurs where the liming of acid soils decreases the concentration of almost all micronutrients except molybdenum. But this decrease varies from nutrient to nutrient. For example, Cu is more strongly complexed by soluble organic matter than Zn (Hodgson et al., 1966), and effects of increasing soil pH are more marked on Zn uptake than on Cu uptake by plants (Robson and Pitman, 1983). The second form of interaction is between ions whose chemical

properties are sufficiently similar that they compete for site of adsorption, absorption, transport, and function on plant root surfaces or within plant tissues. Such interactions are more common between nutrients of similar size, charge, geometry of coordination, and electronic configuration (Robson and Pitman, 1983). This type of interaction is common among Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}.

In crop plants, the nutrient interactions are generally measured in terms of growth response. When plant growth is taken into consideration, interactions may be positive or negative. When nutrients in combination result in a growth response that is greater than the sum of their individual effects, the interaction is positive; when the combined effect is less, the interaction is negative. In the former case the nutrients are synergistic, whereas in the latter they are antagonistic. Additivity indicates the absence of interaction (Sumner and Farina, 1986).

4.3.5.4 Environment

Environmental factors such as moisture supply, temperature, and light affect nutrient concentrations in plants. Since weather varies from year to year in a given agroclimatic region, nutrient concentrations vary in crop plants from year to year. This variation is more significant in annual shallow-rooted crops due to greater variability in moisture supply (Bates, 1971). Soil moisture plays an important role in movement of nutrients to roots and hence absorption and concentration in the plants. Fisher (1980), working with *Stylosanthes humilis* in Australia, found that P concentrations in shoots were reduced from 0.20% to as low as 0.08% by water stress during early vegetative growth and from 0.22% to 0.15% during late vegetative growth.

When temperature is below the optimum, plant growth is reduced. As a result nutrient concentrations in the dry matter tends to increase (Bouma, 1983). In subterranean clover grown at three temperatures (15°C day/10°C night, 21°C day/16°C night, 27°C day/22°C night), and at two P levels, the response in growth to increasing P level was least at the lowest temperature. The P concentration in all plant parts was highest at the lowest temperature and decreased with rising temperature (Bouma and Dowling, 1969). There is potentially a limit at which further decreases in temperature will not cause a further rise in nutrient concentration or may even cause a decrease (Bouma, 1983). Light influences nutrient concentrations in a similar manner.

4.4 VISUAL SYMPTOMS

Identification of nutritional disorders in crop plants through visual symptoms is the cheapest diagnostic technique. However, considerable experience is needed on the part of the observer to identify nutritional disorders through visual symptoms. Visual symptoms are sometimes confused with disease, insect, and drought stress. The first step in identifying nutrient disorder by visual symptoms is observation of the growth and development of the plant. Growth can be stunted by deficiency or toxicities of all elements, but nitrogen and phosphorus are two important nutrients whose deficiency brings about growth reduction. The second step is to note what plant part is affected. Whether the foliar symptoms appear on the lower leaves or older leaves or on the stem, flowers, and growing points of the plant depends on the nutrient. After identifying the part of the plant, the third step is recognition of the nature of the symptoms whether chlorotic, necrotic, or deformed.

If symptoms appear on the lower leaves, there exists the possibility of deficiency of mobile nutrients such as N, P, K, Mg, and Zn. Mobile nutrients are those that can be retranslocated within plants. They move from the original site of deposition (older leaves) to the organ where the nutrient is in demand, normally because of active growth in that organ. As a result, deficiency will first be observed on older leaves on the lower portion of the plant. When a shortage of an immobile element occurs, the element is not translocated to the growing region of the plant but remains in the older leaves where it was originally deposited. Deficiency symptoms, therefore, first appear on the young upper leaves of the plant. Immobile elements include Ca, Fe, S, B, Mn, and Mo. Tables 4.16 and 4.17 describe some important key points in the identification of symptoms of nutrient deficiency or toxicity symptoms in crop plants.

TABLE 4.16
General Description of Nutrient Deficiency Symptoms in Field Crops

Nutrient	Symptoms
N	Chlorosis starts in old leaves; in cereals tillering is reduced; under field conditions, if deficiency is severe, whole crop appears yellowish and growth is stunted
P	Growth is stunted; purple orange color of older leaves; new leaves dark green; in cereals tillering is drastically reduced
K	Older leaves may show spots or marginal burn starting from tips; increased susceptibility to diseases, drought, and cold injury
Ca	New leaves become white; growing points die and curl
Mg	Marginal or interveinal chlorosis with pinkish color of older leaves; sometimes leaf-rolling-like drought effect; plants susceptible to winter injury
	Chlorosis of younger leaves; under severe deficiency whole plant becomes chlorotic and similar to appearance in N deficiency
Zn	Rusting in strip of older leaves with chlorosis in fully matured leaves; leaf size is reduced
Fe	Interveinal chlorosis of younger leaves; under severe deficiency whole leaf becomes first yellow and finally white
Mn	Similar to iron deficiency; at advanced stage necrosis develops instead of white color
Cu	Chlorosis of young leaves, rolling, and dieback
Mo	Mottled pale appearance in young leaves; bleaching and withering of leaves
B	Pale green tips of blades, bronze tint; death of growing points

TABLE 4.17
General Descriptions of Toxicity Symptoms in Field Crops

Nutrient/Element	Symptoms
N	Plants usually dark green in color with abundant foliage, but usually with a restricted root system; NO_3 toxicity shows marginal burn of older leaves followed by interveinal collapse; NH_4^+ toxicity produces blackening around tips of older leaves and necrosis
P	Necrosis and tip dieback; interveinal chlorosis in younger leaves; marginal scorch of older leaves
K	Excess K may lead to Mg and possibly Mn, Zn, and Fe deficiency
S	Reduction in growth and leaf size; sometimes interveinal yellowing or leaf burning
Mg	Excess Mg can induce K deficiency
Fe	Common in flooded rice plant on acid soils; bronzing of older leaves; induced P, K, and Zn deficiency
B	Interveinal necrosis
Mn	Yellowing beginning at the leaf edge of older leaves; uneven chlorophyll distribution; interveinal bronze-yellow chlorosis in beans
Cl	Burning of leaf tips or margins; reduced leaf size, sometimes chlorosis
Zn	Excess zinc induces iron chlorosis in plants
Cu	Stunting, reduced branching, induced iron chlorosis
Mo	Rarely observed
Al	Yellowing with white interveinal stripe on older leaves

The N and P deficiency symptoms in rice and dry bean plants are shown in Figures 4.10 through 4.17. Similarly, K, Zn, and Fe deficiency symptoms in upland rice are shown in Figures 4.18 through 4.25. For further information, there are several publications that describe the foliar symptoms of nutritional disorders in crop plants and illustrate them with color photography (Wallace, 1961; Chapman, 1966; Bergmann and Neubert, 1976; Wilcox and Fageria, 1976; Bould et al., 1983; Fageria, 1984).

FIGURE 4.10 **(See color insert following page 138.)** Upland rice growth at 0, 150, and 300 mg N kg^{-1} soil.

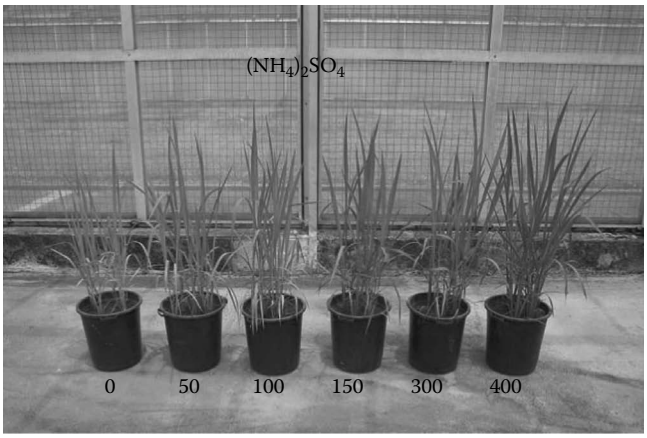

FIGURE 4.11 Upland rice growth at different N rates. The N deficiency symptoms at lower N rates (0, 50, and 100 mg N kg^{-1} soil).

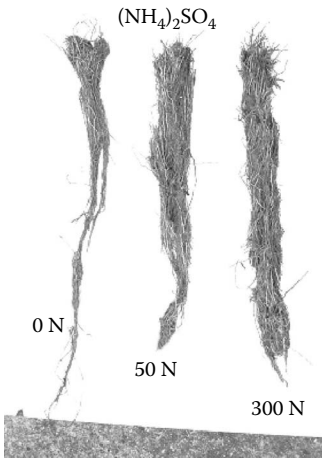

FIGURE 4.12 Upland rice root growth at three N rates (0, 50, and 300 mg kg^{-1} of soil).

FIGURE 4.13 **(See color insert following page 138.)** Dry bean plants without N (left) and with N (right).

FIGURE 4.14 **(See color insert following page 138.)** Upland rice plants without P at left, with 100 mg P kg^{-1} at center and with 200 mg P kg^{-1} at right.

4.5 CROP GROWTH RESPONSE

Soil and plant analyses are the common practices for identifying nutritional deficiencies in crop production. The best criterion, however, for diagnosing nutritional deficiencies in annual crops is through evaluating crop responses to applied nutrients. If a given crop responds to an applied nutrient in a given soil, this means that the nutrient is deficient for that crop. Relative decrease in yield in the absence of a nutrient, as compared to an adequate soil fertility level, can give an idea of the magnitude of nutrient deficiency. This can be done by conducting experiments under greenhouse and/or field conditions.

FIGURE 4.15 Upland rice plants with 25 mg P kg^{-1} at left and with 200 mg P kg^{-1} at right.

Fageria (1994) conducted a greenhouse experiment that provides evidence of which major nutrient is most limiting for five important annual crops in an Oxisol of central Brazil. The results are presented in Figure 4.26. It can be concluded from the data presented in Figure 4.26 that phosphorus was the most yield-limiting nutrient among the three nutrients evaluated for all the crops tested. This means that, in an Oxisol, phosphorus deficiency is the primary yield-limiting nutrient for annual crop production. Among the crops tested, the upland rice growth was the lowest without P treatment, as compared to the treatment that received N, P, and K. These results also suggest that crop species differ in their susceptibility to P deficiency. Crops can be classified for P deficiency susceptibility in the order of upland rice > wheat > common bean > corn > soybean.

FIGURE 4.16 Root growth of upland rice at 25 and 200 mg P kg^{-1} soil.

4.6 CORRECTION OF NUTRIENT DISORDER

After having diagnosed a nutrient disorder, the next step is to correct it in order to improve crop production. Methods of correcting nutrient deficiencies or toxicities vary according to agroclimatic regions, the socioeconomic situation of the region, the magnitude of the disorder, and the nutrient or element involved. A generalized description of these methods is presented in Tables 4.18 and 4.19. Use of efficient or tolerant cultivars in combination with fertilizers or amendments may be the best solution for correcting nutrient disorders in field crops, but

FIGURE 4.17 Dry bean plants without P (left) and with P (right).

FIGURE 4.18 Upland rice without K (left) and with K (right).

FIGURE 4.19 **(See color insert following page 138.)** Potassium deficiency symptoms in upland rice plants.

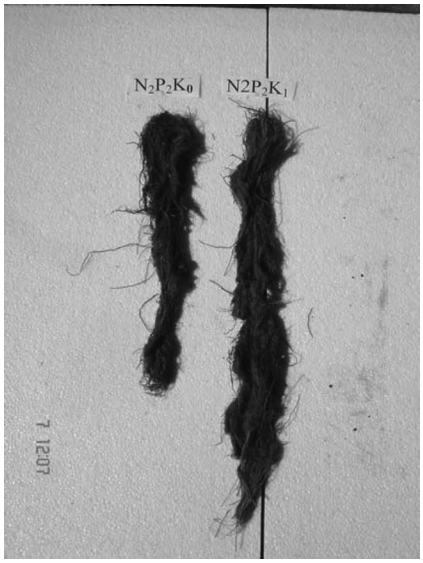

FIGURE 4.20 Upland rice root growth without K (left) and with K (right).

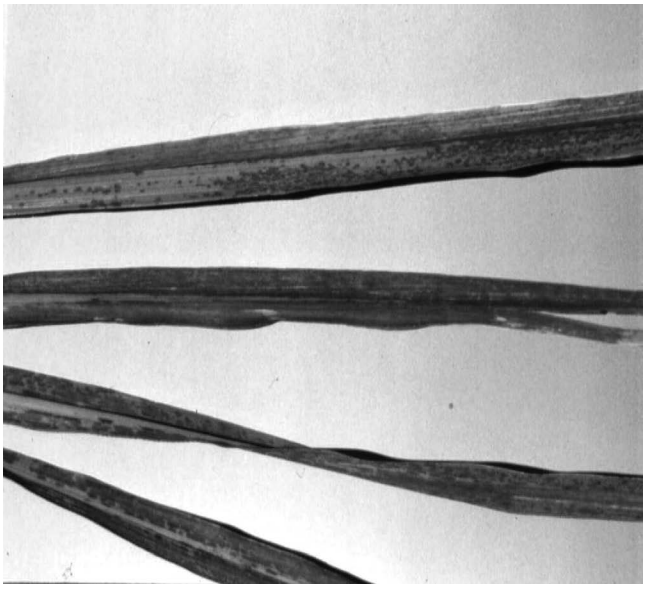

FIGURE 4.21 **(See color insert following page 138.)** Zinc deficiency symptoms in rice leaves.

this will vary according to the situation. Fertilizer recommendations are usually based on results of field trials in which crop response to various rates of fertilizer application is determined. Such response curves provide relationships between yield and the amount of fertilizer required for a particular crop grown in a particular agroclimatic region. From such curves, economic rates of fertilizer use can be derived. In such calibration studies, it is important that all other controllable crop production factors are at optimum levels.

FIGURE 4.22 **(See color insert following page 138.)** Zinc deficiency symptoms in upland rice plants.

FIGURE 4.23 **(See color insert following page 138.)** Upland rice plants without Fe deficiency (left) and with Fe deficiency (right).

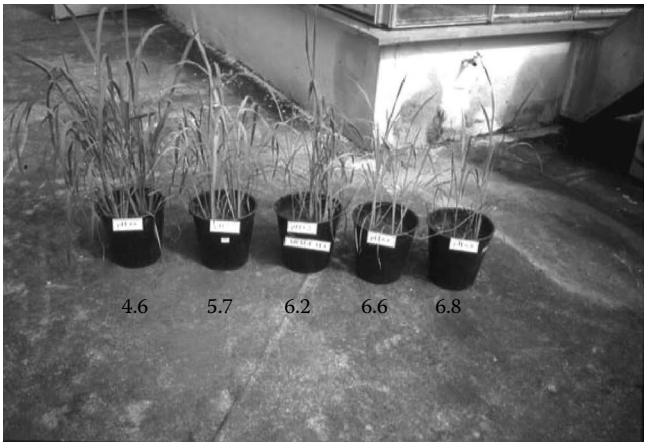

FIGURE 4.24 **(See color insert following page 138.)** Iron deficiency in upland rice when soil pH was raised from 4.6 to 6.8.

FIGURE 4.25 Iron deficiency in upland rice grown on Brazilian Oxisol.

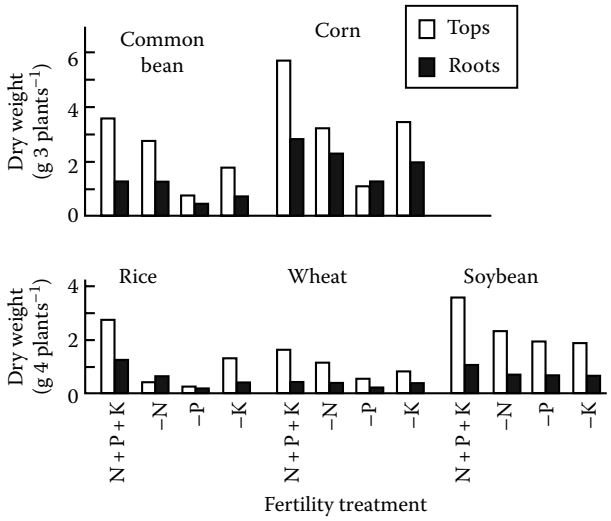

FIGURE 4.26 Comparison among five crops in dry matter production of tops and roots under different fertility treatments. (From Fageria, N.K., *Better Crops Int*., 10, 8, 1994.)

Figure 4.27 shows a quadratic relationship between N rate and grain yield of lowland rice grown on a Brazilian Inceptisol. In fertilizer experiments, the amount of fertilizer required to produce 90% of the maximum yield is often considered as an economical rate (Fageria et al., 2003). In this case, 90% of the maximum grain yield was obtained with the application of 136 kg N ha^{-1} (Figure 4.27). Singh et al. (1998) reported that maximum average grain yield of 20 lowland rice genotypes was obtained at 150–200 kg N ha^{-1}. Similarly, Dobermann et al. (2000) reported that 120–150 kg N ha^{-1} for field experiments in the dry season at the International Rice Research Institute in the Philippines. Similarly, Figure 4.28 presents results of P rates and grain yields of lowland rice grown on a Brazilian Inceptisol. Grain yield significantly increased in a quadratic fashion with increasing P rate in the range of 0–87 kg ha^{-1} (0–200 kg P_2O_5 ha^{-1}). Based on regression equations, maximum grain yield was obtained at the 55 kg P ha^{-1} or 125 kg P_2O_5 ha^{-1}.

TABLE 4.18
Methods of Correcting Nutrient Deficiency and Al and Mn Toxicity

Nutrient/Element	Corrective Measures
N	Addition of organic matter to the soil; application of N fertilizers, including legumes in the crop rotation; use of foliar spray of 0.25%–0.5% solution of urea
P	Adjustment of extreme pH; application of phosphorus fertilizers
K	Application of potassium fertilizers, incorporation of crop residues
Ca	Liming of acid soils; addition of gypsum or other soluble calcium sources where lime is not needed; foliar spray in acute cases with 0.75%–1% calcium nitrate solution
Mg	Application of dolomitic limestone; foliar application of 2% magnesium sulfate solution
S	Use of fertilizer salt containing sulfur such as ammonium sulfate and single superphosphate; application of gypsum or elemental sulfur
Zn	Addition of zinc sulfate to soil; foliar spray of 0.1%–0.5% solution of zinc sulfate
Fe	Foliar spray of 2% iron sulfate or 0.02%–0.05% solution of iron chelate; use of efficient cultivars
Cu	Soil application of copper source of fertilizer or foliar spray of 0.1%–0.2% solution of copper sulfate
B	Soil application of boron source or foliar spray of 0.1%–0.25% solution of borox
Mo	Liming of acid soils, soil application of sodium or ammonium molybdate; foliar spray of 0.07%–0.1% solution of ammonium molybdate
Mn	Foliar application of 0.1% solution of manganese sulfate
Al/Mn	Application of lime; use of tolerant species or cultivars

TABLE 4.19
Tolerance of Plant Foliage to Mineral Nutrient Sprays

Nutrient	Formulation or Salt	kg 400 L^{-1}[a] of Water
Nitrogen	Urea	3–5
	NH_4NO_3, $(NH_4)_2HPO_4$, $(NH_4)_2SO_4$	2–3
	NH_4Cl, $NH_4H_2PO_4$	2–3
Phosphorus	H_3PO_4, others see N above	1.5–2.5
Potassium	KNO_3, K_2SO_4, KCl	3–5
Calcium	$CaCl_2$, $Ca(NO_3)_2$	3–6
Magnesium	$MgSO_4$, $Mg(NO_3)_2$	3–12
Iron	$FeSO_4$	2–12
Manganese	$MnSO_4$	2–3
Zinc	$ZnSO_4$	1.5–2.5
Boron	Sodium borate	0.25–1
Molybdenum	Sodium molybdate	0.1–0.15

Sources: Compiled from Wittwer, S.H., Foliar application of nutrients—Part of the chemical revolution in agriculture, Plant Food Review 2, National Plant Food Institute, Washington, DC, 1967; Fageria, N.K. et al., *J. Plant Nutr.*, 32, 1044, 2009.

[a] 400 L of solution is sufficient to spray on 1 ha of field crop.

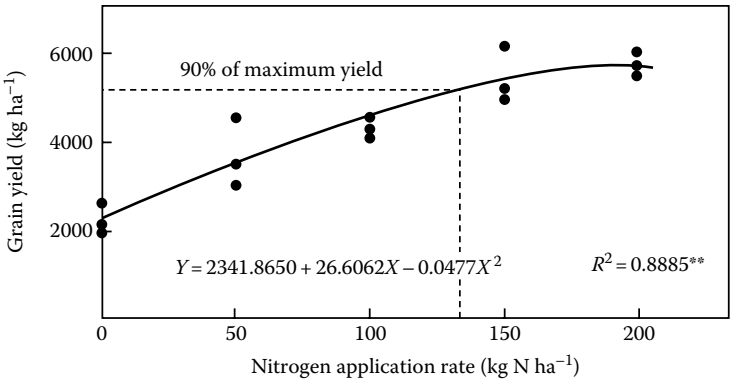

FIGURE 4.27 Grain yield of lowland rice as influenced by nitrogen application rate. Values are averages of 12 genotypes and 2 years field trial. (From Fageria, N.K. et al., *J. Plant Nutr.*, 31, 788, 2008b.)

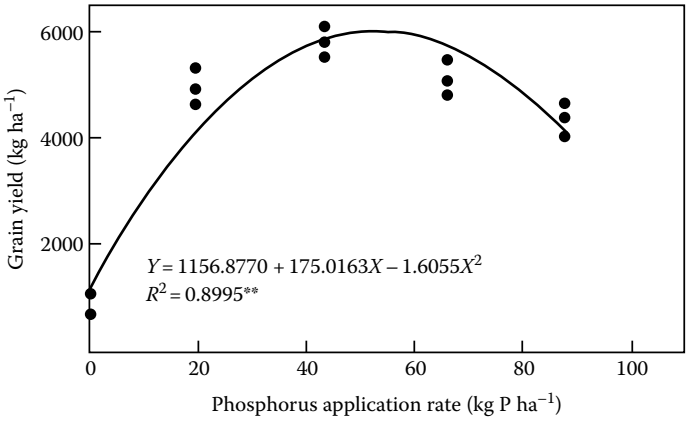

FIGURE 4.28 Relationship between phosphorus application rate and grain yield of lowland rice grown on Brazilian Inceptisol. (From Fageria, N.K. et al., *J. Plant Nutr.*, 31, 1121, 2008a.)

4.7 SUMMARY

Soil testing, plant analysis, visual foliar symptoms, and crop growth response are the most common guides to the fertilization of field crops. Among these diagnostic techniques, visual symptoms are the least expensive, but soil analysis is widely used for soil fertility evaluation. Quantities of fertilizer and lime are determined on the basis of soil test calibration studies for each crop in a given agroclimatic region. One of the greatest values of tissue analysis is in the prevention of deficiencies rather than their correction after they appear. Thus, trends in tissue analysis over a period of years may be studied in relation to the fertilizer programs to determine whether the supply of one or more elements is deficient, adequate, or excessive in a particular soil for a particular crop. Soil analysis, plant analysis, and visual symptoms are all useful and complementary in nutritional diagnosis of crop plants. The three techniques provide information for evaluating the nutrient status of the soil–plant environment and for establishing the basis for fertilizer and lime applications.

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5 Nutrient Management of Degraded Soils

5.1 INTRODUCTION

Soil is a key natural resource and soil quality is one of the most important properties that determines crop productivity and sustainability. Good soil quality not only produces good crop yields but also maintains environmental quality and consequently plant, animal, and human health (Fageria, 2002). One of many uses and roles of soil is its function as a filter. Soils can sequester large amounts of pollutants before they threaten biological organisms or the healthfulness of food (Cook and Hendersot, 1996; Oliver, 1997; Sojka and Upchurch, 1999). Soil is a dynamic, living resource whose condition is vital both to the production of food and fiber and to the ecosystem function or, in essence, to the sustainability of life on earth (Doran et al., 1996). Soil is the base upon which society is built (Singer and Warkentin, 1996). Good soil is a critical resource for civilization, as it makes possible the shift from nomadic societies to stable communities (Smith and Lee, 2003). In the early days, soil productivity was totally dependent on natural resources, and there was a sound ecological equilibrium among soils, plants, animals, and humans. However, the situation began to change with the advancement of agricultural science and technology. Use of agricultural machinery, irrigation, fertilizers, pesticides, good quality seeds, and intensive cultivation created disequilibria between soil and plant ecosystems, and soil quality started declining. A significant decline in soil quality has occurred worldwide, creating a need to develop criteria to evaluate soil quality and to take corrective actions (Fageria, 2002).

The world's arable land resources are finite and nonrenewable on a human timescale. Arable land is the primary medium for food and fiber production for mankind. The world's total land area is about 13.4 billion ha. Crops are planted on about 1.4 billion ha, and another 0.12 billion ha are under perennial crops around the world. In addition, about 3.5 billion ha are under pastures used for animal production. These areas together represent about 37% of the world's total land area. Further, about 31% of the total land area is under forests, with the remainder devoted to populated areas, roads, recreational, and waste areas.

Soil degradation affects about 35% of the earth's land surface (Mabbutt, 1984). It has been suggested that historically more land has been forced out of crop production because of soil degradation than the amount of land in crop production at the present time (Larson, 1986). It has been estimated that 0.3%–0.5% (4–7 million ha) of the world's crop land is being taken out of production each year, and that the rate of degradation is accelerating. It is projected that, by the end of the century, 10 million ha (0.7%) will be lost each year (FAO, 1983). Soil productivity in developing countries may be reduced by one-fifth (Dudal, 1982). If these projections are approximately correct, the amount of land lost to crop production may approach the amount of new lands that can be brought into productivity. Archaeological evidence suggests that many ancient civilizations vanished because of a decline in soil productivity due to degradation (Lal, 1989). The decrease in productivity depends on the stage of soil degradation (Figure 5.1). There is always a threshold of soil degradation that causes a reduction in crop or animal productivity.

Mengel (1993) stated that global resources are declining and environmental pollution is increasing in an exponential manner. According to Buringh (1982), within 100 years no potential cropland will be left unused worldwide. Schnepf (1979) reported that the production potential of American land is limited and that there is a real need to protect prime land, that is, good agricultural land,

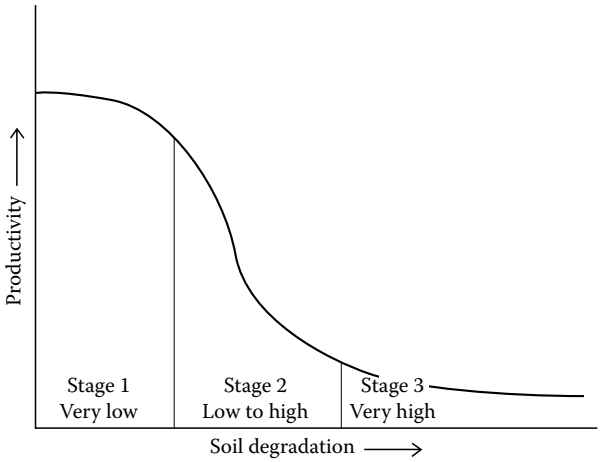

FIGURE 5.1 Relationship between soil degradation and productivity. (Modified from Lal, R. et al., *Land Degrad. Rehabil.*, 1, 51, 1989. With permission.)

because it is one of the most important resources of the country. Boyle et al. (1989) and Smith and Elliott (1990) have described cropping practices in the last several decades that have degraded the soil resource and caused ever-diminishing crop yields.

Hillel and Rosenzweig (2005) reported that a crucial imperative is to ensure the adequate production and supply of food for growing populations in a world in which biotic, terrestrial, and aquatic resources have already been seriously degraded or depleted. The world's average population density of 45 people per km^2 is projected to rise to 66 people per km^2 by 2050 (Hillel and Rosenzweig, 2005). Since only about 10% of land is arable, population densities per unit of arable land are roughly 10 times higher (Cohen, 2003). In this context, progress of the present as well as future generations depends on conservation of our valuable soil resources. Due to continuously increasing world demand for more food and fiber, farmers have to use the best existing technologies, and agricultural scientists have to develop new technologies to arrest or minimize future degradation of arable lands and restore already degraded lands for crop production.

Fortunately, human population growth seems to be slowing, and agriculture has already begun to develop and adopt better methods of production coupled with biological control and conservation, aimed at preserving, even restoring, degraded soils (Edwards et al., 1993; Smith et al., 1995; Hillel and Rosenzweig, 2002). The objective of this chapter is to discuss the causes of soil degradation and suggest management practices to minimize degradation processes and assure sustainable crop production.

5.2 DEFINITIONS OF SOIL DEGRADATION AND SUSTAINABLE SOIL MANAGEMENT

The United Nations Environment Program (UNEP, 1982) defines soil degradation as the decline in soil quality caused by its use by humans. According to FAO (1978), soil degradation is the diminution of the current and/or potential capability of soil to produce (quantitative or qualitative) goods or services as a result of one or more degradation processes. Lal et al. (1989) defined soil degradation as diminution of soil quality and/or reduction in its ability to be a multipurpose resource due to both natural and man-induced causes. In the agricultural sense, soil degradation leads to loss of sustainable production (Lal et al., 1989). Hillel and Rosenzweig (2002) reported that land desertification in arid, semiarid, and dry subhumid areas resulting from various factors, including climate variations and human activities, is also known as land degradation. Thus, there are several definitions of soil degradation in the literature. Based on all these definitions, we propose a simple definition

of soil degradation. For our purposes, soil degradation is the deterioration of soil physical, chemical, and biological properties due to disturbances in its original environment that limit its ability to sustain efficient farming systems.

According to Smith et al. (1993), soil quality may be defined in several different ways including productivity, sustainability, environmental quality, and effects on human nutrition. Doran and Parkin (1994) and the Soil Science Society of America (1997) defined soil quality as the capability of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health. The quality of a soil is largely defined by soil function and represents a composite of its physical, chemical, and biological properties that provide a medium for plant growth, regulate and partition water flow in the environment, and serve as an environmental buffer in the formation, attenuation, and degradation of environmentally hazardous compounds (Fageria, 2002). Parr et al. (1992) defined soil quality as the capability of a soil to produce safe nutritious crops in a sustained manner over the long-term, and to enhance human and animal health, without impairing the natural resource base or harming the environment. Karlen et al. (1997) defined that soil quality is the capacity of a soil to function in an ecosystem to support plants and animals, resist erosion, and reduce negative impacts on associated air and water resources. The meaning and quantification of soil quality depend on chemical, physical, and biological parameters. Of these, the biological measurements are least understood (Kennedy and Papendick, 1995). As a complex functional state, soil quality may not be directly measurable, but may be inferred from measurable indicators of soil quality (Islam and Weil, 2000).

To quantify soil quality, specific soil indicators need to be measured spatially. These indicators are mainly soil properties whose values relate directly to soil quality but may also include policy, economic, or environmental considerations (Smith et al., 1993).

Similarly, many definitions for sustainable land management have been proposed (Bouma, 1994). However, we feel that at present the best definition is that proposed by an International Working Group for the development of an international framework for evaluating sustainable land management. "Sustainable land management combines technologies, policies and activities aimed at integrating socioeconomic principles with environmental concerns so as to simultaneously maintain or enhance production and services; reduce the level of production risks; achieve environmental stability by preserving soil and water quality; and be economically viable and socially acceptable" (Dumanski et al., 1991).

5.3 PROCESSES AND/OR FACTORS OF SOIL DEGRADATION

Soil degradation processes include chemical, physical, and biological actions and interactions that affect a soil's capability for self-regulation. Due to degradation, the soil's physical, chemical, and biological properties deteriorate and soil can no longer sustain efficient farming systems. Selected indicators of soil quality and some processes they impact are presented in Table 5.1. Some of these properties are quite ephemeral and can be modified easily with routine management practices or weather. Others are permanent properties inherent to the soil profile or site and are little affected by management. A management-oriented soil quality assessment would focus on properties that are intermediate between these two extremes. Since conservation management is designed to enhance soil quality, a useful soil quality index would include properties enhanced by conservation management (Fageria, 2002). In this section, soil degradation processes and/or factors are discussed, and management strategies for each degradation process are suggested. The result should be a sustainable soil environment that can support efficient crop and animal production without degrading soil and water resources.

5.3.1 Physical Degradation

Physical soil degradation is related to changes in soil physical, mechanical, hydrological, and rheological properties that have a negative effect on crop and animal production, farm income, and

TABLE 5.1
Selected Soil Properties Contributing to Soil Quality

Soil Property	Process Affected
Bulk density	Plant root penetration, water- and air-filled pore space, and biological activity
Aggregation	Soil structure, erosion resistance, crop emergence, and infiltration
Infiltration	Runoff and leaching potential, plant water-use efficiency, and erosion potential
Slope	Water infiltration, soil erosion, and cultivation practices
Topsoil depth	Rooting volume for crop production, and water and nutrient availability
Conductivity or salinity	Water infiltration, crop growth, and soil structure
pH	Nutrient availability, pesticide absorption, and mobility
Organic matter	Nutrient cycling, pesticide and water retention, and soil structure
Available nutrients	Capacity to support crop growth and environmental hazard
Microbial biomass	Biological activity, nutrient cycling, and capacity to degrade pesticides
Mineralogy	Nutrient uptake, pesticide adsorption, and water-use efficiency of crop plants

Source: Modified after Karlen, D.L. et al., *Soil Sci. Soc. Am. J.*, 61, 4, 1997.

environmental quality (Lal et al., 1989). Deterioration of soil physical properties along with deforestation, burning of vegetation, monoculture, and overgrazing of pasture lands may lead to soil degradation. These degradation processes or factors are reviewed in this section.

5.3.1.1 Deterioration of Soil Structure

Soil structure refers to the arrangement of primary soil particles into secondary particles or aggregates. Soil structure, per se, is a qualitative concept. Soil structure can be defined operationally as the interaction between soil solids and soil pores (Gupta et al., 1989). Decline in soil structure eventually leads to surface sealing, crusting, compaction, hardsetting, reduction in permeability, poor aeration, and waterlogging. Well-structured soils and soils with macropores and fractures provide a pore network for root growth (Logsdon and Cambardella, 2000) and water infiltration, often resulting in little or no yield reduction, even when the soil is compacted (Lowery and Schuler, 1991). A few studies have shown that moderate compaction may benefit crop yield, especially during dry years (Johnson et al., 1990), because of better seed–soil contact and better soil continuity contributing to capillary rise of water to the root zone (Fageria, 2002).

5.3.1.1.1 Surface Sealing or Crusting

Dispersion and subsequent illuviation of fine particles into pores has often been suggested as a major process causing formation of soil crusts (Bresson and Cadot, 1992). The concept of washing-in, plugging of large pores by washed-in fine material, was introduced by McIntyre (1958a,b) to describe crust formation under rainfall. Surface sealing increases the probability of runoff and soil erosion and occurs on many soils worldwide (Ewing and Gupta, 1994). Rainfall and sprinkler irrigation often cause a surface seal or crust, especially when the soil surface is bare. Surface seals generally range from 2 to 3 mm thick and are sometimes overlain by a skin seal (0.1 mm in thickness) composed almost entirely of fine particles (Tarchitzky et al., 1984). This seal reduces infiltration of water into the soil and thus increases the probability of runoff, erosion, and surface water pollution. Surface sealing from rains that occur after planting and before seedling emergence also hampers stand development. The formation of a thin, dense surface layer is a product of the combined effects of aggregate breakdown and soil particle rearrangement due to raindrop impact. The mechanisms of seal formation have not been fully delineated, but some contributing processes have been identified. The underlying cause appears to be dispersion of clay (Shainberg et al., 1989), which weakens the soil. Southard et al. (1988) reported that clay disperses because of a decrease in electrolyte

concentration of the soil solution during rainfall. LeBissonais (1990) stated that in dry soils, the initial aggregate breakdown is caused by slaking, while in wet soils, raindrop impact is the cause.

The flocculation of suspended soil colloids plays an important role in the processes of surface crust formation (Southard et al., 1988). Dispersed soil particles have a negative impact on soil structure and contribute to soil erosion and contaminant movement. Flocculation at a given soluble bivalent cation charge fraction was increased as the organic C content of the soil colloids decreased (Goldberg et al., 1990). Low organic matter content and a high proportion of silt are associated with crust formation. FAO (1978) developed an index to characterize soils with these properties:

$$\text{Crusting index} = \frac{\%\ \text{fine silt} + \%\ \text{coarse silt}}{\%\ \text{clay}}$$

This index will exceed 2.5 for soils prone to intense crusting. An index based on soil organic matter content also used by FAO (1978) is

$$\text{Crusting index} = \frac{1.5\ (\%\ \text{fine silt}) + 0.75\ (\text{coarse silt})}{\%\ \text{clay} + 10\ (\text{organic matter})}$$

This index will exceed 2 for soils prone to intense crusting.

5.3.1.1.1.1 Surface Sealing or Crusting Management Strategies Many factors have been related to seal formation including soil texture, aggregate stability, organic matter content, surface coverage by residue, cropping and tillage systems, and rainfall percolation (Chiang et al., 1993). Organic matter appears to be a dominant factor controlling soil particle flocculation, and consequently crust formation. Available experimental evidence suggests that organic matter stabilizes mineral particles in suspension (Goldberg et al., 1990; Miller et al., 1990; Ryan and Gschwend, 1990). The effect of organic matter on the flocculation of soil particles is often explained in terms of particle charge. Dixit (1982) concluded that adsorption of organic matter onto clay particles increases their negative charge and, therefore, suspension stability. Goldberg et al. (1990) concluded that organic matter decreased the flocculation of soil particles through an effect on particle charge. Thus, maintaining adequate levels of organic matter in the soil is an important strategy to reduce soil sealing or crusting. The most important management practice to reduce this problem is to maintain vegetative or crop residue cover on the soil surface.

5.3.1.1.2 Soil Compaction

Soil compaction refers to the compression of unsaturated soils, during which an increase in the density of the soil body and a simultaneous reduction in fractional air volume occurs. According to the Soil Science Society of America (1997), soil compaction is the process by which the soil grains are rearranged to decrease void space, thereby increasing bulk density. Soil compaction is often characterized in terms of bulk density, void ratio, or total porosity (Gupta et al., 1989). Compaction effects on soil degradation are due to changes in soil physical, chemical, and biological processes. These processes in turn are dependent on the soil structure. In addition to chemical toxicity, physical barriers in the soil profile can also limit root penetration and proliferation (Alcordo and Recheigl, 1993). These include natural hardpans, dense B horizons, and tillage pans formed by heavy machinery (Bowen, 1981). Sidhu and Duiker (2006) reported significant reduction of corn yield in compacted soil compared to no-tillage without compaction.

5.3.1.1.2.1 Compaction Management Strategies Soil compaction can be reduced by improving soil organic matter content, keeping the soil surface covered with vegetation, use of conservation or minimum tillage, and preparing soil at an appropriate moisture level. Subsoiling is the process of

deep tilling to a depth ranging from 30 to 90 cm (Roa-Espinosa, 1998). It has shown some success in alleviating compaction and improving yields on soils with compacted subsoil (Reeves et al., 1992; Chen et al., 2005; Sidhu and Duiker, 2006). In addition, application of gypsum may increase subsoil root development and reduce compaction. For example, Sumner et al. (1990) presented mechanical impedance and aggregate stability data that they claimed demonstrated that application of both mined gypsum and phosphogypsum to highly weathered soils improved penetration of subsoil hardpans by roots. Similarly, Radcliffe et al. (1986) showed that mechanical impedance was lower on gypsum-treated soils that had been cropped for several years than on fallowed plots. They concluded that gypsum increased subsoil root activity, which in turn reduced subsoil mechanical impedance.

5.3.1.1.3 Soil Erosion

Loss of topsoil by wind and water erosion caused by poor soil management is by far the largest single factor contributing to deterioration of soil physical, chemical, and biological properties and decline in productivity of most cropland soils. Eroded soils decrease crop yields through increased bulk density, poor tilth, and reduced organic matter content, nutrient availability, and water-holding capacity (Arriaga and Lowery, 2003; Izaurralde et al., 2006). The altered properties of eroded soils reduce plant growth by altering root density patterns, crop growth rates, and developmental stages (Izaurralde et al., 2006). Reduced crop growth and development create, in turn, opportunities for greater weed growth and reduced crop yields. Izaurradle et al. (2006) reported that grain yield reduction of various crops like wheat, barley, and canola on eroded soil was either a linear or curvilinear function of nutrient removal. The magnitude of the effect of erosion on yields also varies among soils, crops, and management practices (Lal, 1987). Soil erosion by water depends primarily on soil detachment by raindrop impact (splash) and the transport capacity of the sheet flow. Erosion models have separated water erosion into two components: rill and interrill erosion. Runoff from the soil surface may concentrate in small erodible channels known as rills. In rill erosion, soil loss is due mainly to detachment of soil particles by flowing water (Ben-Hur et al., 1992). In interrill erosion, soil detachment is caused by raindrop impact, and soil transport is due to raindrop splash and runoff flow (Watson and Laflen, 1986). The detachment capacity of interrill flow is small because of its low velocity (Young and Wiersma, 1973). Raindrop detachment capacity is high because the kinetic energy of raindrops has been estimated to be 260 times that of surface flow (Hudson, 1971). However, most of the sediment removed from the interrill area is transported by runoff flow (Young and Wiersma, 1973). In addition to soil detachment, the beating action of raindrops causes the development of a seal at the soil surface (Levy et al., 1994). Seal formation in soils exposed to raindrop impact is due to two mechanisms (Agassi et al., 1981): (1) physical disintegration of soil aggregates and their compaction and (2) physicochemical dispersion and movement of clay particles into a region of 0.1–0.5 mm depth, where they lodge and clog the conducting pores. The two mechanisms act simultaneously as the first enhances the latter. The seals formed are layers less than 2–3 mm thick that have a greater density, higher shear strength, and lower saturated conductivity than the underlying soil (Levy et al., 1994). Seal strength, as inferred from surface pitting by impacting raindrops, decreases with an increase in clay content and is inversely related to soil erosion (Levy et al., 1994).

Soil loss depends on the inherent susceptibility of the soil to erosion and is called soil erodibility (Wischmeier and Smith, 1978). Slope steepness is an important factor governing water erosion. For nonerodible soils, soil loss doubles as slope steepness increases from 5% to 30% (Watson and Laflen, 1986). For erodible soils, increasing slope from 5% to 30% increases erosion by severalfold (Warrington et al., 1989). Nowak et al. (1985) estimated the mean annual soil loss in the United States (average of sheet, rill, and wind erosion) to be 15.3 Mg ha^{-1} $year^{-1}$ for cropland, 5.9 Mg ha^{-1} $year^{-1}$ for pasture, and 2.7 Mg ha^{-1} $year^{-1}$ for forest land. Such quantitative information is not available for other countries, especially those in the tropical and subtropical region where demographic pressures are high and where soils are highly susceptible to erosion and are of low inherent fertility (Lal, 1987).

The U.S. Department of Agriculture (USDA) has assigned a soil loss tolerance value (*T*-value) for most cultivated soils. This value defines the maximum rate of soil loss that will still permit sustained crop production. These *T*-values never exceed 11.2 Mg ha^{-1} year^{-1}, and some are less, depending on the soil depth and other factors (Larson, 1981). Nationally, soil erosion by water alone exceeded the *T*-value on more than 45.3 million ha or on 27.1% of the cropland (Larson, 1981). Water caused annual sediment discharge of 15.9 Mg ha^{-1} in the cultivation of winter wheat in the Southern Great Plains (Smith et al., 1991). Water erosion and runoff are serious factors in soil degradation of the loamy soils of northern and western Europe. The main damage is related to the accumulation of excess surface water and the concentration of runoff in rills and gullies during rain storms (Courault et al., 1993).

5.3.1.1.3.1 Erosion Control Measures Some management practices, such as maintaining or increasing soil organic matter, in turn will reduce compaction and improve other soil properties like infiltration, water retention, and aeration. Conservation tillage systems offer tremendous potential for erosion control as well as for conserving water and increasing organic matter content of some soils. Dickey et al. (1984) reported that no-tillage systems reduced water erosion by 95% during the fallow period of a wheat-fallow rotation. Conservation tillage systems generally range from practices that retain a minimum of 30% surface cover after planting to a complete lack of mechanical tillage that preserves most plant residues on the soil surface after harvest of plant parts of economic value (Conservation Technology Information Center, 1988). Conservation tillage systems are extensively used in major U.S. agroecosystems for soil erosion control (Dao, 1993).

Various types of soil cover have been shown to be effective in reducing water as well as wind erosion potential (Figure 5.2). When 60% of the soil is covered by nonerodible material, the soil loss ratio (soil loss from protected soil/soil loss from flat, bare soil) is nearly zero. Even a small amount of soil cover is very important. For example, if a bare field had a potential soil erosion loss of 20 t ha^{-1} year^{-1}, 10% soil cover on that field would reduce potential soil losses to 12.9 Mg ha^{-1} year^{-1}. A 20% cover would reduce potential loss to 8.3 Mg ha^{-1} year^{-1}, and a 30% cover would reduce losses to 5.4 t ha^{-1} year^{-1} (Bilbro and Fryrear, 1994). After harvesting, much of the residue of many crops such as sorghum, corn, millet, and rice will be standing. Standing residue is superior to flat residue in decreasing potential wind erosion (Figure 5.3). Figure 5.4 shows the effect of vegetative cover in intercepting rainfall energy and soil erosion control. When 20% of the soil surface was covered with vegetative cover, the water erosion rate was only 30%; and when 60% of the surface was covered with vegetative cover, water erosion was practically zero.

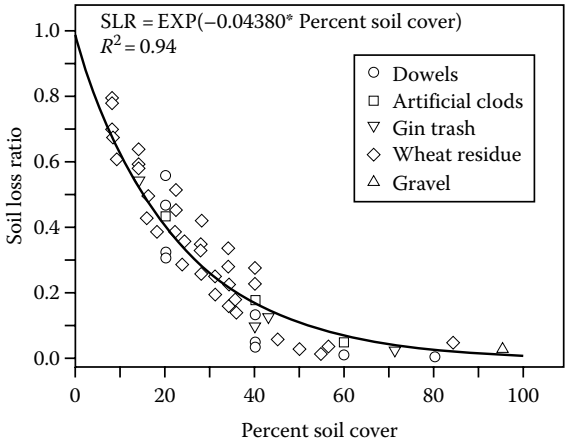

FIGURE 5.2 Soil loss ratio as a function of percent of soil covered by nonerodible material. (From Bilbro, J.D. and Fryrear, D.W., *Agron. J.*, 86, 550, 1994. With permission.)

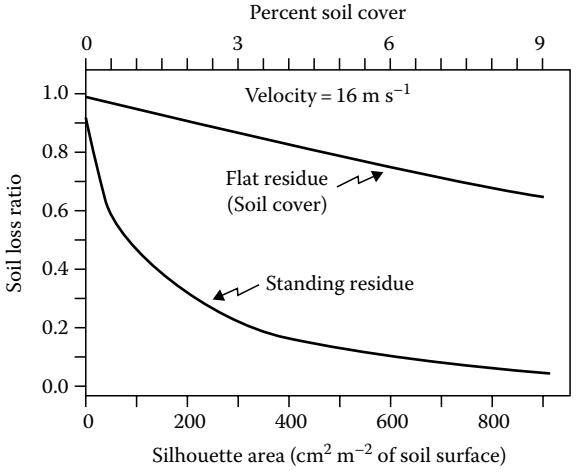

FIGURE 5.3 Soil loss ratios for flat and standing residue. (From Bilbro, J.D. and Fryrear, D.W., *Agron. J.*, 86, 550, 1994.)

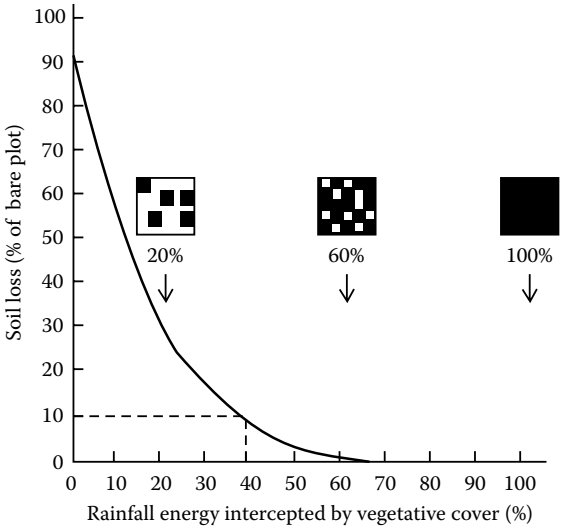

FIGURE 5.4 Relationship between rainfall energy interception by vegetative cover and soil erosion by water. (From Shaxson, T.F., Improving productive potential of tropical soils, in *Paper Presented at 24th Brazilian Soil Science Congress*, Golante-GO, Brazil, July 25–31, 1993.)

Furrow diking or basin tillage is the practice of constructing small earthen dams within furrows to increase surface water retention, thus preventing runoff and increasing infiltration (Jones and Stewart, 1990). Deep tillage is another water conservation method that increases soil permeability and reduces runoff and erosion. Detailed descriptions of soil erosion control measures are given by Lal (1984, 1986). Nitrogen and P fertilizers have been used to restore the productivity of eroded soils (Tanaka and Aase, 1989; Malhi et al., 1994; Izaurralde et al., 2006).

5.3.1.1.4 Drought

Water deficiency is one of the most important soil degradation factors in arid and semiarid regions. Arid climate is defined as receiving 250 mm or less average annual precipitation, while semiarid regions receive between 250 and 500 mm of precipitation annually (Stephens, 1994). Together these

two regions comprise about 35% of the earth's surface, excluding the polar deserts (Potter, 1992). Occurrence of drought is the common phenomenon in arid and semiarid regions. Drought can also occur in humid regions. For example, in central Brazil, the average annual rainfall is about 1500 mm, mainly concentrated during October to March. This amount is sufficient to produce two annual crops. However, a 2–3 week drought during the rainy season is very common in this region (Fageria, 1980). Sometimes drought occurs at a sensitive crop growth stage such as flowering, and crop yields are significantly reduced. This means that rainfall distribution during the crop growth cycle is just as important as total rainfall. Similarly, water shortage is the primary factor limiting crop production in the west-central Great Plains of the United States, and agricultural sustainability depends on efficient use of water resources (Stone and Schlegel, 2006).

5.3.1.1.4.1 Drought Management Strategies Supplementary irrigation during the rainy season and permanent irrigation during the dry period are two of the best solutions for coping with drought stress, thereby reducing soil degradation. China and India have approximately 45 and 43 million ha of irrigated land, respectively, representing about 40% of the world's irrigated area. Irrigation is one of the most important technological factors that made these countries self-sufficient in food supply, allowing them to support about 37% of the world population. Irrigation in some areas makes farming possible; in others, it supplements rainfall.

However, it is not possible in all droughty regions to provide irrigation due to water scarcity or economic reasons. Other management practices, such as improving the infiltration rate of soil through deep plowing, use of mulching to reduce evaporation from the soil surface, planting drought-resistant crops or cultivars, and other complementary solutions, may reduce the impacts of drought in unirrigated crops. Use of appropriate crop rotations can also increase the efficiency of water use. In parts of southern and central Great Plains of the United States, one wheat and one sorghum crop are produced in a 3 year period, with a fallow period of about 330 days following each crop. These fallow periods afford an opportunity for increasing storage of precipitation as soil water, thus reducing dependency on irrigation and providing some additional water for achieving more favorable yields under limited irrigation or dryland conditions (Unger, 1992). The percentage of precipitation stored as soil water increases with increasing amounts of crop residue retained on the soil surface during fallow (Unger, 1984; Wilhelm et al., 1986). Similarly, Groenevelt et al. (1989) have pointed out that relatively thin surface layers of gravel and coarse sands can reduce evaporation to 10%–20% of that occurring from recently wetted, unmulched soil surfaces. Low ridges (shallow furrows) can also increase infiltration (Unger, 1992). As described above, additional water conservation is possible by using furrow dikes or blocked furrows to capture potential runoff water (Jones and Stewart, 1990).

Improving water-use efficiency is an important strategy in water-limited environments to improve crop yields. Improved water-use efficiency can be gained by decreased tillage, increased residue on the soil surface, reduced length of fallow periods, contour farming, furrow dikes, disruption of plowpans, and selection of more drought-tolerant crops and crop rotations (Nielsen et al., 2005; Stone and Schlegel, 2006).

5.3.1.1.5 Deforestation

Expansion of cropland areas to meet the needs of rapidly rising human and livestock populations has resulted in increased deforestation (Kang et al., 1990). Deforestation and forest conversion are major factors of soil degradation (Harrison, 1984). Each year, 14 million ha of primary forest disappear (Sanchez et al., 1991). Shifting cultivation is responsible for almost 70% of deforestation in tropical Africa (Kang et al., 1990). In tropical South America, after clearing the land, upland rice is generally planted for 1–3 years, followed by pasture. The unfavorable effects of deforestation and cropping on soil microclimate, soil physical and chemical properties, and biotic components have been widely reviewed and investigated (Lal, 1986; Kang et al., 1990). Deforestation is also decimating the world's largest repository of plant and animal diversity.

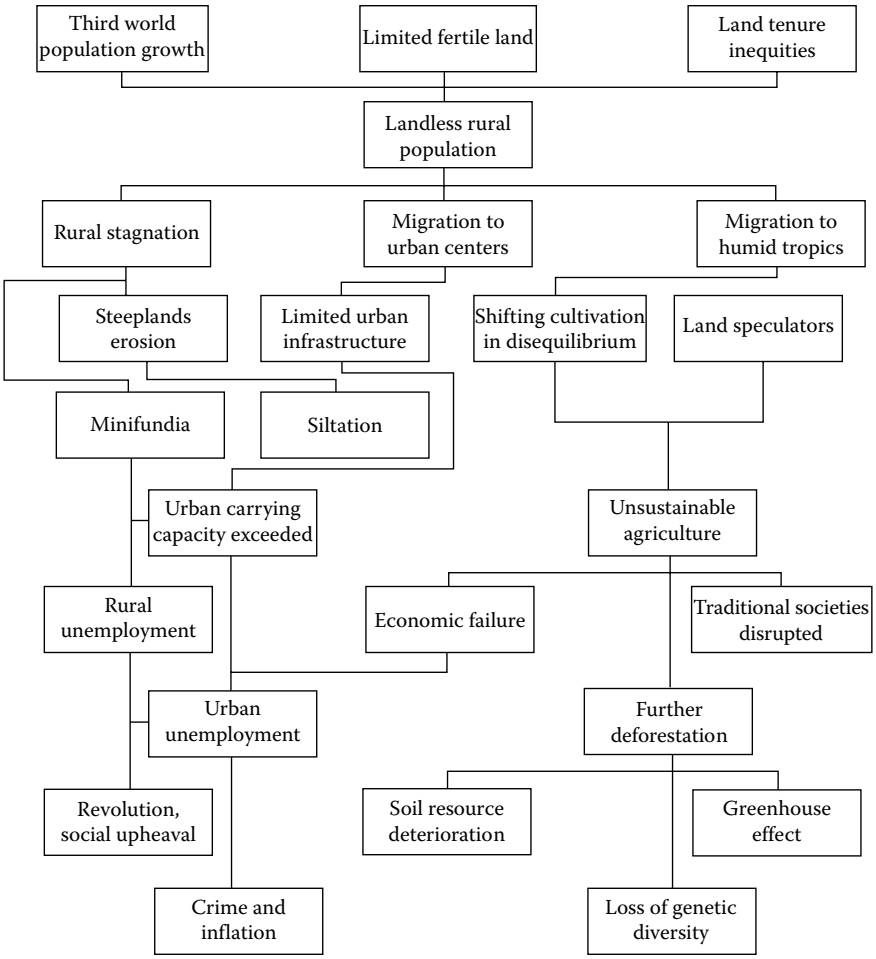

FIGURE 5.5 Cause–effect relationships related to tropical deforestation in developing countries. (From Sanchez, P.A. et al., Alternative to tropical deforestation, in Tropsoils technical report 1988–1989, North Carolina State University, Raleigh, NC, 242–246, 1991.)

Tropical deforestation is driven by a complex set of demographic, biological, social, and economic forces (Figure 5.5). Deforestation is one of the main reasons for the global net release of CO_2 from soil to the atmosphere (Veldkamp, 1994). Soil-vegetation systems can act as a CO_2 sink or a CO_2 source, depending on decomposition rate and rate of soil organic carbon (SOC) formation (Van Breemen and Feijtel, 1990). When forest is cleared, the soil turns into a CO_2 source. The annual relative increase in global atmospheric CO_2 concentration is 0.5%, which corresponds to 3.6 Pg C $year^{-1}$ (Bouman, 1990). Estimates of global CO_2 release caused by deforestation are between 1.0 and 3.2 Pg C $year^{-1}$. Recent estimates indicate that about 18% of all global warming is caused by release of carbon dioxide as the result of clearing of tropical rain forests (Sanchez et al., 1991). Recent concern for global climate change has created a heightened interest in the role of forested ecosystems in the global C cycle. Globally, 1576 Pg of C (1576×10^5 g) is stored in soils, with 506 Pg (32%) of this in soils of the tropics (Eswaran et al., 1993a). It is also estimated that 40% of the C in soils of the tropics is in forest soils (Eswaran et al., 1993a). Deforestation followed by 25 years of pasture caused a net loss of 21.8 Mg ha^{-1} in soil organic C for an Eutric Hapludand and 1.5 Mg ha^{-1} for an Oxic Humitropep (Veldkamp, 1994). Detwiler (1986) estimated that cropping of tropical forest soils reduced their C content by 40%; the use of these soils for pastures reduced their C content by about 20%.

Other studies have shown that deforestation can result in 20%–50% loss of this stored C, largely through erosion (Eswaran et al., 1993a).

5.3.1.1.5.1 Strategies to Reduce Deforestation and Its Impacts Land management options that improve the economic status of subsistence farmers, maintain agricultural productivity on deforested lands, and recuperate productivity of degraded lands are urgently needed. These options must be compatible with the various socioeconomic needs in the region so that they are readily and widely adopted. Sanchez et al. (1991) describe some of the main management options:

1. Land clearing that does not damage the soil.
2. Use of low-input cropping systems on infertile arid soils such as Oxisols and Ultisols.
3. Use of agroforestry for much of the humid tropics because it can be adapted to a wide range of socioeconomic and soil-landscape conditions.
4. Developing grass–legume pastures which can provide sustainability for cattle production.
5. Use of effective crop rotations and the judicious application of lime and fertilizers.
6. Maximization of nutrient cycling in order to minimize the need for external nutrient inputs. The management of crop and root residues is essential in this regard.

5.3.1.1.6 Wetlands

Types of soil wetness include short-term wetness caused by excessive rainfall or flooding, groundwater table rise caused by irrigation and canal seepage, perched shallow watertables caused by soil compaction, groundwater table rise due to land surface management, and impeded surface drainage due to construction of highways (Fausey and Lal, 1990). Measurements of hydrology, vegetation, and soils constitute the three-parameter approach that is currently favored by the federal government for delineating wetlands in the United States (Federal Interagency Committee for Wetland Delineation, 1989). A wetland protected by law must meet the criteria listed for hydric soils by the Soil Conservation Service (1991) and Megonigal et al. (1993). A hydric soil is one that is saturated, flooded, or ponded long enough during the growing season to develop anaerobic conditions in the upper part (Soil Conservation Service, 1991).

In soil taxonomy, wet soils are identified by an aquic moisture regime at the suborder level or by properties used to define an aquic soil moisture regime. A soil that is saturated with water and essentially depleted of oxygen is defined as having an aquic moisture regime. A reducing environment, a result of stagnant water, persists for a sufficient time for aerobic microorganisms to deplete soil oxygen. As the reducing environment is extended, organisms extract chemically bound oxygen. The most accurate methods for demonstrating hydric conditions involve monitoring soil moisture, watertable fluctuations, soil O_2 content, reduction–oxidation potential, or Fe^{2+} activity (Faulkner and Patrick, 1992; Megonigal et al., 1993).

The annual flooding of the Paraguay River and its meandering tributaries such as the Cuiba, Itiquira, Taquari, and Miranda is responsible for the name "Pantanal," a large swampland in Portuguese. During the November through March rainy season, the flooding plains begin filling and ephemeral lakes take shape. Permanent lakes are connected one to another and to tributaries by temporary streams. The Pantanal's total area is about 15 million ha, covering much of the states of Mato Grosso and Mato Grosso de Sul of Brazil and some adjoining territory of Paraguay and Bolivia.

The Everglades represent a unique and complex composite of ecosystems forming a vast wetland covering a large portion of Southeastern Florida in the United States. The original Everglades encompassed an area of about 1 million ha (Debusk et al., 1994). In Southeast Asia, millions of hectares of land in coastal swamp areas have been and are being reclaimed for agriculture (Konsten et al., 1994). A large part of the 25 million ha of coastal swamp soils in Indonesia has only limited potential for agriculture (Nedeco/Euroconsult, 1984).

There are many diverse effects of soil wetness. One of these is anaerobiosis, a very significant effect from an agronomic or biological perspective. The major physical change that can be defined

as soil degradation associated with soil wetness is loss of soil strength. The chemical effects of soil wetness that can be associated with soil degradation are accumulation of salts at or near the surface in semiarid or arid regions under high watertable conditions and changes in solubility and chemical form of nutrients under anaerobic conditions (Fausey and Lal, 1990). In their original waterlogged state, many of these soils contain pyrite. If the soils are reclaimed and drained, pyrite oxidation results in acidification of soil and water; acid sulfate soils then develop (Dent, 1986). Low nutrient content, low pH, and relatively high contents of dissolved Al and Fe, organic acids, and H_2S are responsible for poor crop performance on many young sulfate soils (Konsten et al., 1994).

5.3.1.1.6.1 Reclamation of Wetlands Among reclamation measures, adequate drainage is one of the most effective, but expensive, control measures. The drainage system may be surface or subsurface. The use of drainage to ameliorate excessive soil wetness has long been a subject of study (USDA, 1987). Drainage is not a guarantee against soil degradation by wetness, but drainage can minimize periods of anaerobiosis, improve trafficability, aid in flushing salts, and reduce soil erosion (Fausey and Lal, 1990). The use of soil ridges or ridge tillage has been reported as an alternative tillage method to alleviate high soil water content and low soil temperatures on poorly drained soils (Radke et al., 1993).

5.3.1.1.7 Crop Monoculture versus Crop Rotation

Monoculture is defined as growing a single crop year after year. Monoculture usually requires large amounts of inputs such as fertilizers, pesticides, and machinery. Repeatedly growing the same crop on the same land can produce "soil sickness," which is thought to be caused by a combination of soil pathogens, mineral depletion, change in soil structure, and accumulation of toxic substances. Johnson et al. (1992) reported that spore populations of mycorrhizal fungi, which proliferated in corn monoculture, generally correlated negatively with yield and tissue mineral concentrations of corn but were positively correlated with the yield and tissue mineral concentrations of soybean. Continuous monoculture of both corn and soybean generally had lower yields and tissue concentrations of P, Cu, and Zn than first-year crops. Crop rotation is a system of growing different types of crops in a recurrent succession and in an advantageous sequence on the same land (Bullock, 1992). The practice of crop rotation dates back to the Han Dynasty of China more than 3000 years ago (MacRae and Meheys, 1985), and the Romans recognized the benefits of alternating leguminous crops with cereals more than 2000 years ago (Karlen et al., 1994; Robson et al., 2002). Modern crop rotation was established around 1730 in England, and became known as the Norfolk four-course rotation (Wibberley, 1989; Lampkin, 1990; Bullock, 1992). This development marked the movement toward the reduction or elimination of fallow periods and the inclusion of roots and clover into the rotations (Bullock, 1992; Robson et al., 2002).

Crop rotations may increase yields by decreasing the incidence of disease and improving soil physical properties and fertility. For example, rotation of soybean and corn increases the yield of both crops when compared with monoculture production (Pedersen and Lauer, 2002, 2003; Temperly and Borges, 2006). Bhowmik and Doll (1982) reported that soybean yielded an additional 10%–15% when rotated with corn compared with continuous soybean. Katsvairo et al. (2006) reported that most beneficial effects of rotations are realized with crop diversification. These authors reported that using perennial grasses such as bahiagrass (*Paspalum notatum* Fluegge) or bermudagrass (*Cynodon dactylon* L. Pers.) in a traditional peanut–cotton rotation can increase yields, improve soil properties, and increase farm profits. These authors further reported that including grazing livestock in the cropping system makes more efficient use of climate and farm resources by extending the period of productive plant growth, improving economic returns, and reducing risk by diversifying the products available for sale.

Detailed crop rotation experiments in the Netherlands demonstrated that yields of wheat, and especially of potato, decreased over the years and stabilized at different levels depending on the frequency of crop rotation. Potatoes grown in the same plots every fourth (1:4) or every third (1:3)

year have yielded 10–15 lb (5–7 kg) less, in general, than potatoes grown every sixth year (a 1:6 potato-cropping frequency). Yields were even lower (30% less) in fields where potatoes had been cropped every second year or every year (Schippers et al., 1987). Legume and meadow-based rotations and conservation tillage systems often maintain more favorable soil properties compared with monocultures and plow-based methods (Lal et al., 1994; Meyer-Aurich et al., 2006). Meadow and leguminous cover crops are believed to improve soil structure and increase soil fertility (Power, 1990; Lal et al., 1990). Dick et al. (1986) observed that rotation significantly improved corn grain yield, with corn yields in a corn–oat–meadow rotation averaging 1.22 Mg ha^{-1} more than in continuous corn and 0.96 Mg ha^{-1} more than in a corn–soybean rotation.

Havlin et al. (1990) found that increasing the frequency of corn and sorghum with soybean increased surface organic C and N, especially under no-tillage. After only 3.5 years of no-tillage, wheat–corn–millet-fallow rotations had greater surface organic C and N concentrations and potential mineralization than wheat-fallow rotations on soils that had previously been managed under conventional tillage for 50 or more years (Wood et al., 1990). Crop rotation increased yields, increased profitability via diversification, and decreased environmental risks due to reduced chemical inputs (Pierce and Rice, 1988).

Although crop rotation may improve mineral nutrition, particularly of N, there may also be a rotation effect beyond that which can be explained by fertility alone (Copeland and Crookston, 1992). At Urbana, Illinois, high rates of limestone and N, P, and K fertilizers did not substitute for rotation, which increased yield of corn rotated with soybean by 16% over corn grown in monoculture (Welch, 1976). In rotation studies at Lancaster, Wisconsin, in which N was not limiting, the 8 year average yields for continuous corn were less than the average yield for first-year corn (Higgs et al., 1976).

Lampkin (1990) and Robson et al. (2002) enumerated principal characteristics of a successful crop rotation, which are

1. Rotate deep and shallow rooting crops to improve soil structure, aeration, water-holding capacity, and drainage.
2. Alternate crops with large and small root biomass to increase nutrient uptake from both deep and shallow depths.
3. Rotate N_2-fixing and N-demand crops to meet cropping system N demands within the system.
4. Alternate weed-susceptible and weed-suppressing crops to interrupt weed life cycles.
5. Grow crops with different pest and disease tolerance to break pest and disease cycles, and reduce the presence of host plants in the rotation.
6. Grow catch crops, green manures, and undersow crops to maintain soil cover to reduce erosion and nutrient leaching.
7. Alternate autumn- and spring-sown crops to control weeds and distribute workload.
8. Balance forage and cash crops to make rotation economically as well as ecologically viable.

5.3.1.1.8 Monoculture versus Intercropping

Like crop rotation, intercropping is another management practice to improve degraded soils. Intercropping is the practice of growing two or more different crops together on the same field at the same time. Such practice can improve the use of resources like nutrients and water and reduces risks of insects, diseases, and weeds (Willey, 1979; Vandermeer, 1989; Liebmann and Dyck, 1993; Szumigalski and Acker, 2006). Intercrops have been observed to compete more efficiently for nutrients than sole crops, thereby preempting weeds in the use of these resources (Abraham and Singh, 1984; Hauggaard-Nielsen et al., 2001). The apparent increase in resource use efficiency of intercrops suggests that these systems could be useful in low input or organic farming systems where options for chemical crop inputs are limited or nonexistent (Szumigalski and Acker, 2006). The most commonly used intercropping systems combine legumes with cereals. Legumes can fix

atmospheric nitrogen that can later be used by nonlegume crops (Vandermeer, 1989; Anil et al., 1998). Another advantage of intercropping is that legume crops can absorb large amount of N that could be leached out of the system and supply it to the nonlegume companion crop later or to a subsequent crop (Vandermeer, 1989; Midmore, 1993; Szumigalski and Acker, 2006).

In the north central United States, legume crops are normally sown into established cereal grain nurse crops. For example, cereal grains have been used historically to establish 85% of the alfalfa fields in Iowa (Tesar and Marble, 1988; Blaser et al., 2006). Spring-seeded oats is the companion crop of choice in this region (Tesar and Marble, 1988; Blaser et al., 2006). Introducing a winter cereal grain/red clover intercrop into corn–soybean rotation can provide producers with crop alternative that can diversify income (Exner and Cruse, 2001; Blaser et al., 2006), improve yields of subsequent crops with reduced inputs (Singer and Cox, 1998), improve soil quality (Reicosky and Forcella, 1998), and disrupt pest cycles (Cook, 1988; Blaser et al., 2006).

5.3.1.1.9 Overgrazing

Grazing is an important element in most pasture ecosystems since it interacts with and determines the structure and composition of vegetation (Anderson, 1990; Hobbs et al., 1991). Overgrazing tends to reduce root growth and rhizome carbohydrate reserves (Turner et al., 1993). The decrease of below-ground C inputs could result in a reduced C/N ratio of below-ground plant biomass, reduced microbial growth, and reduced potential for N immobilization (Holland and Detling, 1990).

Overgrazing can denude the land of vegetation and cause severe erosion by wind and water in humid, semiarid, and arid regions. Livestock numbers in Africa increased from 295 million animals compared with 219 million people in 1950 to 520 million animals compared with 515 million people in 1983 (Lal, 1988). Although a high proportion of these livestock animals were of poor quality and low productivity, they often exceeded the carrying capacity of the land, thereby accelerating degradation (Lal, 1988). Similarly, in the Thar desert of Rajasthan, India, a large number of animals (especially sheep, goats, and camels) denuded the scanty vegetation, causing soil degradation by wind erosion in the extremely dry periods of May and June.

5.3.1.1.9.1 Overgrazing Management Strategies The best management strategy is rational and controlled grazing of pastures. Research can determine how many animals should be grazed per unit area and time. During the rainy season, adequate fertilization should be applied and grazing pressure should be limited to allow pasture species to recover. If a pasture is adequately managed, it not only supports good animal production but also reduces environmental pollution. For example, the internal N cycle of grassland and prairie ecosystems has been shown to accumulate little NO_3 in the soil profile because of high plant and microbial activities (Jackson et al., 1989; Schimel et al., 1989). Jackson et al. (1989) studied short-term N turnover in a grassland ecosystem to demonstrate that microbes actually outcompete plants for available NO_3 and NH_4. This ability of microorganisms to rapidly immobilize available NO_3 and NH_4 is dependent on the presence of a readily available C source. Schimel (1986) described a higher level of N immobilization in prairie soils than in cultivated soils and attributed this difference to the quality and quantity of C substrate available for microbial use in the prairie soil.

5.3.1.1.10 Surface Mining

Exploration and surface mining of precious metals and minerals degrade sizable land areas in various parts of the world. It has been estimated that 4 million ha of land in the United States have been disturbed as a result of surface mining for coal (Doolittle and Hossner, 1988). Texas, the nation's sixth largest coal-producing state, could potentially have more than 400,000 ha disturbed by surface mining for lignite (Clarke and Baen, 1980). The extensive volume of overburden material generated from mining is generally disposed of on the land surface near the site. This spoil material, composed of regolith and bedrock, degrades the soils and presents a challenge for reclamation.

5.3.1.1.10.1 Management Strategies Successful reclamation of surface-mined land can be accomplished by using a mixed overburden-topsoil substitute. Mixed overburden has been found to form mine-soils that have better chemical and physical properties than pre-mine-soils (Bearden, 1984). When properly managed, mine-soils from mixed overburden have an excellent yield potential (Doolittle et al., 1994).

Schuman and Sedbrook (1984) demonstrated that abandoned bentonite mine spoils could be successfully reclaimed using sawmill wastes (wood chips, bark, and sawdust) as a spoil amendment that enabled immediately improved water infiltration, which allowed successful reestablishment of perennial vegetation. Schuman and Meining (1993) reported that surface-applied gypsum at the rate of 56 Mg ha^{-1} effectively ameliorated bentonite mine spoil under natural rainfall conditions in a semiarid environment.

Colonization of vegetation by vesicular arbuscular mycorrhizal fungi may enhance plant growth and P cycling during reclamation of mined lands (White et al., 1992). Sutton and Dick (1987) have given a detailed description of management processes adopted for the reclamation of acid mined lands in humid areas.

5.3.1.1.11 Vegetation Burning

Wild fires, prescribed burning, and slash burning are common in various parts of the world. For example, burning pasture and forest land for crop planting is a very common practice in South America in the dry period of July, August, and September. In tall grass prairies, a major ecosystem in the United States, fire is a common disturbance (Garcia and Rice, 1994). Vegetation burning changes physical, chemical, and biological properties of a soil and enhances the risk of degradation. However, deterioration depends on intensity and duration of fire. Subjective methods for classifying burns based on litter and on soil appearance after fire have been described by Chandler et al. (1983). Low-intensity or lightly burned areas are characterized by black ash, scorched litter, low plant mortality, and maximum surface temperature during burning of 100°C–250°C. Moderate burning produces surface temperatures of 300°C–400°C and consumes most of the plant material, thus exposing the underlying soil which otherwise is not altered. High-intensity or severe burning produces surface soil temperatures in excess of 500°C and is recognized by white ash remaining after the complete combustion of heavy fuel and by reddening of the soil.

Prescribed burning is a vegetation management tool that removes plant cover, producing variable effects on infiltration, surface runoff, and erosion (Knight et al., 1983; Lloyd-Reilley et al., 1984). Prescribed burning of vegetation may increase the potential for surface runoff and erosion. Emmerich and Cox (1994) reported that immediately after a rangeland burn, runoff and sediment production may be unchanged; but within 1 year, significant increases can occur, probably due to soil surface morphological changes during the 1 year time period.

Soil texture changes have been observed in response to both fires and laboratory heating. Ulery and Graham (1993) found a significant decrease in the clay content of severely burned soils and a corresponding increase in sand, suggesting the aggregation of clay-sized particles into stable sand-sized secondary particles, but no evidence other than mechanical analysis has been shown. Ulery and Graham (1993) also reported that in the reddened layers, organic C was reduced by 90%–100%, while in the blackened layers, it was reduced by 15%–68%, compared with the unburned surface soil. Sertsu and Sanchez (1978) noted almost total elimination of organic C when soils were heated in the laboratory to 400°C.

Schwertmann and Fetcher (1984) suggested that goethite, a yellowish-brown Fe oxide, nearly ubiquitous in soils, can be transformed to maghemite and hematite during a fire, especially if organic matter is present, which contributes to an O_2-deficient environment.

Litter and aboveground standing biomass serve to maintain high infiltration rates by protecting soil surface aggregates and structure from destruction by raindrop impact, thus reducing crust formation (Thurow et al., 1986). Reduction in soil aggregate sizes after a burn has been shown to occur and persist for more than 5 years (Ueckert et al., 1978).

Fire induces numerous chemical changes in the soil (Raison, 1979). The intensive heat produced by fires, acting on soil organic matter and plant materials, influences soil elemental pools.

Water-soluble substances including Ca^{2+}, Mg^{2+}, K^{+}, NH_4^{+}, Cl^{-}, and SO_4^{2-} increase after fires (Grove et al., 1986; Khanna and Raison, 1986). Intense soil heating can also lead to the formation of hydrophobic compounds, influencing water infiltration (DeBano et al., 1976), formation of organometallic cement on soil mineral particles (Giovannini and Lucchesi, 1983), and structural alteration of the soil humic fraction (Almendros et al., 1988).

Blank et al. (1994) reported that compared with unburned soils, significant decreases in NO_3^{-} and orthophosphate and significant increases in SO_4^{2-}, acetate, formate, oxalate, and glycolate occurred immediately after fire in the 5 cm surface of soil under shrub growth. Concentrations of organic acids in burned soils increased significantly in the weeks following a wildfire. Elevated concentrations of organic acids may influence seed germination, plant establishment, and mineral nutrition. The nature and magnitude of soil chemical changes are a function of a number of factors, including the nature and density of the vegetation community, fire temperature, length of burn, soil water content, and soil texture (Wright and Bailey, 1982).

Some short-term beneficial effects have also been reported by burning vegetation. For example, burning increases the photosynthetic capacity of postburn plant growth and results in changes in soil temperature, water, and nutrient status (Knapp and Seastedt, 1986). Ojima (1987) reported that annual burning resulted in lower soil organic matter but higher plant productivity compared with no burning. This apparent contradiction may be explained by (1) synchronization of nutrient release with plant uptake and microbial activity, (2) extension of the growing season because of earlier soil warming, (3) changes in the rate of ecosystem processes that allow for recovery of volatilized nutrients (N_2 fixation), (4) changes in the utilization of available nutrients, or (5) a combination of all these reasons (Knapp and Seastedt, 1986; Ojima, 1987).

These short-term effects should not cause us to overlook important long-term effects of vegetation burning. Lal (1986) concluded that repeated fires resulted in a change in climax vegetation from forest to savanna. Large trees of the forest have given way to fire-resistant shrubs and grasses, resulting in the widespread occurrence of derived savanna in Africa, Asia, and Latin America where rainfall and climatic factors would normally support forest vegetation.

5.3.2 Chemical Degradation

Chemical degradation is the change in soil chemical properties from a favorable to an unfavorable state, decreasing soil productivity. The process of degradation may occur due to increasing soil acidity, inadequate fertilization, flooding, practicing monoculture for long periods on the same field, soil erosion, accumulation of salts in harmful concentrations, release of allelochemicals, and indiscriminate use of pesticides. Some of these degradation processes are also related to deterioration of soil physical properties through soil erosion, monoculture, and flooding of wetlands, discussed earlier. In this section, soil acidity, mineral stresses, salt-affected soils, and allelopathy are discussed.

5.3.2.1 Nutrient Stress

Nutrient stresses refer to deficiencies of essential plant nutrients as well as toxicities (Fageria and Baligar, 1993; Fageria, 2009). Nutrient deficiencies are more common than toxicities in many arable lands around the world. In the 1980s and 1990s, evidence accumulated that nutrient depletion is a problem in many tropical soils (Dudal, 1982; Lal, 1987; Hartemink, 2002; Fageria, 2009). If nutrient stress is not alleviated, crop yields are decreased and soils cannot support adequate plant growth. Under these situations, soil degradation starts. If the land continues to be used for crop production, crop yields become so low that farmers have to abandon the degraded areas. Approximately one-fourth of the earth's soils are considered to produce some kind of mineral stress in crops (Dudal, 1976). Figure 5.6 shows the importance of N, P, and K nutrient supply for the growth of rice, wheat, corn, soybean, and common bean in an Oxisol of central Brazil. Data presented in this figure provide evidence that P is the most important yield-limiting nutrient in this, like most other Oxisols.

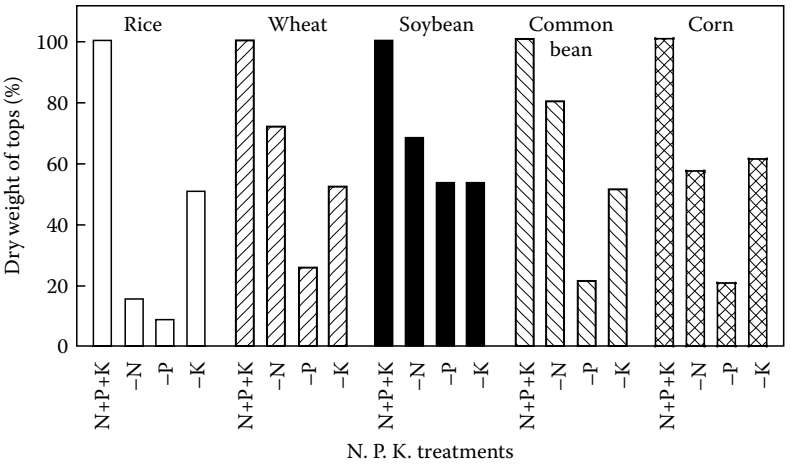

FIGURE 5.6 Comparison among five crops in dry matter production of tops under different fertility treatments. (From Fageria, N.K., *Better Crops Int.*, 10, 8, 1994.)

5.3.2.1.1 Nutrient Management Strategies

Nutrient stresses can be alleviated with adequate fertilizer application. Periodic soil testing helps determine if current nutrient management practices are sustainable. Soil testing is a vital component of sustainable farming programs that are profitable, efficient, and environmentally responsible. A good procedure for making fertilizer recommendations for a given crop on any one soil is to carry out a series of fertilizer trials, fit a response function, and substitute that function into a profit equation to calculate optimal fertilizer levels according to economic variables. Adequate soil fertility reduces soil degradation for the following reasons:

1. Adequate fertility protects the soil from erosion by giving the crop early vigor for quick canopy cover and helps build strong root systems that hold the soil in place.
2. Adequate fertility results in more residues remaining after harvest to protect the soil against wind and water erosion while building organic matter levels and increasing long-term production potential.
3. Adequate soil fertility improves nutrient use efficiency, which is good both economically and environmentally. Balancing nitrogen with phosphate and potassium improves nitrogen use efficiency and leaves less nitrate in the soil, minimizing leaching losses and effects on groundwater.
4. Adequate soil fertility conserves water by reducing the amount required per unit of dry matter production.
5. Adequate soil fertility interacts positively with other production inputs such as tillage practices, variety selection, pest control, and plant population to get the most out of the crop being grown.

In addition to adequate fertilizer amounts, correct placement of fertilizers is an integral part of efficient crop management. Placement can affect both crop yield and nutrient use efficiency (Mahler et al., 1994; Fageria, 2009). Most nutrients such as P and K are banded, and even band application of N is generally preferred over broadcast because (Mahler et al., 1994) (1) fertilizer is placed where small seedling root systems can more readily utilize the nutrients, (2) the amount of fertilizer needed per unit area is lower than with broadcasting, (3) fertilizer is positionally more available to the crop than to germinating weeds, (4) only one operation is needed with planting, and (5) there is less loss of N due to erosion and immobilization. An integrated nutrient management system is

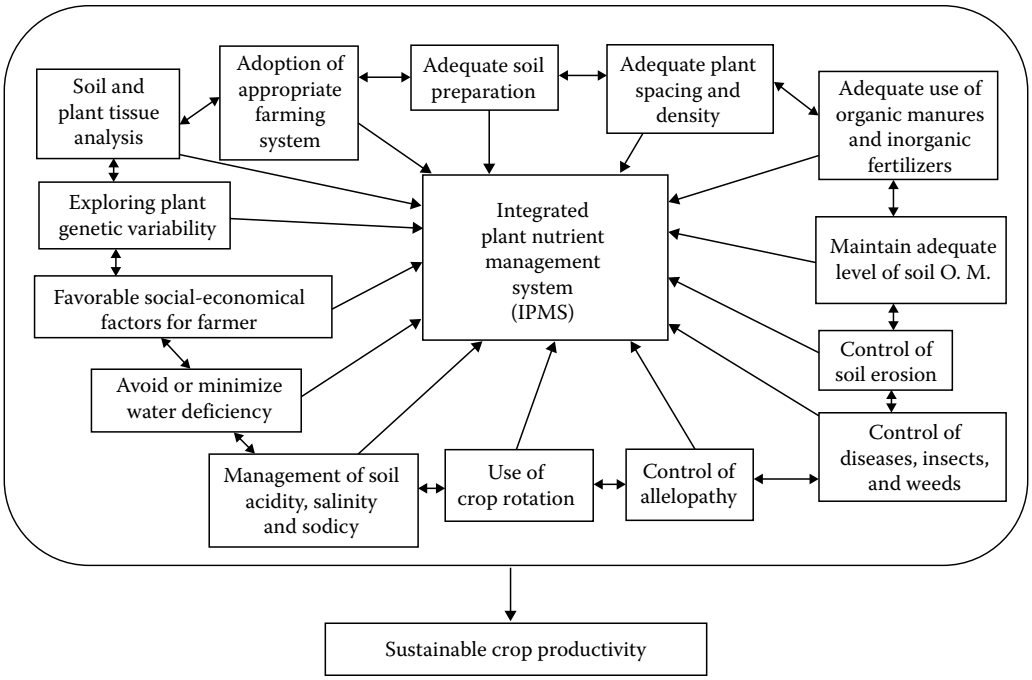

FIGURE 5.7 Integrated plant nutrient management system for sustainable environment.

presented in Figure 5.7. If this system is implemented in any cropping system, nutrient management can be optimized and soil degradation can be reduced to a minimum.

The transformation of extensive rangelands to productive farmland and improved pastureland in the central Brazilian Cerrado has been a quiet social revolution that began in the early 1970s. Management strategies to overcome chemical constraints (nutrient deficiencies and/or elemental toxicities) through appropriate liming, fertilizer rates, and cultivating adapted plant species have developed out of two decades of research on savannah Oxisols in South America coincident with the opening of these lands for agricultural production on a large scale.

In addition to these measures, exploitation of plant genetic variability in absorption and utilization of nutrients is another important strategy to improve nutrient deficiencies and reduce soil degradation. Utilization of plant genetic resources has been the foundation for improvement of agronomic crops. Agricultural scientists around the world have long been using plant genetic resources to develop new crop cultivars that are more productive under environmental stresses. One example of using plant genetic resources is the U.S. National Plant Germplasm System, which maintains large accessions of various crop species (Eberhart, 1993). The 10 International Agricultural Research Centers involved with crops are key institutions for the collection, preservation, and distribution of many agronomically important crops. These centers are CIAT (Colombia), CIMMYT (Mexico), CIP (Peru), ICARDA (Syria), ICRISAT (India), IITA (Nigeria), ILCA (Ethiopia), IRRI (Philippines), WARDA (Ivory Coast), and AVRDC (Taiwan). In addition, many national institutes also maintain large collections of germoplasm of annual crops.

5.3.2.2 Soil Acidity

Soil acidification refers to a complex set of processes that results in the formation of an acid soil (pH less than 7.0) (Robarge and Johnson, 1992; Fageria and Baligar, 2008). According to Krug and Frink (1983), however, soil acidification in the broadest sense can be considered as the summation of

natural and anthropogenic processes that lower measured soil pH. Soil pH is a measure of the activity of H^+ ions in the soil solution, which measures the degree of acidity or alkalinity of a soil. A soil with a pH of 5.0 is 10 times more acidic than one with a pH of 6.0 and 100 times more acidic than one with pH 7.0. Soil acidification cannot be quantitatively described by a single index or parameter, even though it is often assumed that soil pH is such a parameter (Matzner, 1989). Other changes in soils that may occur during soil acidification include loss of nutrients due to leaching, loss or reduction in the availability of certain plant nutrients (such as P, Ca, Mg, and Mo), an increase in the solubility of toxic metals such as Al and Mn, which may influence root growth and nutrient and water uptake, and a change in microbial populations and activities (Binkley et al., 1989; Myrold, 1990). Such changes will often be accompanied by changes in overall soil pH, but the degree of change will be dependent on a combination of properties within a given soil (Robarge and Johnson, 1992; Fageria and Baligar, 2008).

Acidity is a major degrading factor of soils and affects extensive areas both in the tropics and in temperate zones. Acid soils are reported to occupy about 3.0 billion ha, of which over 89% are Oxisols and Ultisols situated in the tropics (Eswaran et al., 1993b). The global distribution of acid soils is 1.17 billion ha Oxisols, 1.13 billion ha Ultisols, 0.48 billion ha Spodosols, and 0.25 billion ha Aridisols (Eswaran et al., 1993b).

In tropical South America, 85% of the region as a whole has acid soils, and there are approximately 850 million ha of underutilized acid soils, undoubtedly the most extensive area of acid tropical soils in the world (Cochrane, 1991). Soil acidity may result from parent materials that were acidic and naturally low in basic cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+) or because these elements have been leached from the soil profile by heavy rains (Fageria et al., 1990a). Soil acidity may also develop from exposure to the air of mine spoils containing iron pyrite (FeS_2) or other sulfides. Crop fertilization with ammonia or ammonium fertilizers can result in soil acidification. In addition, acidity may also be produced by the decomposition of plant residues or organic wastes into organic acids. This process is of particular importance in many forest soils. The important yield-limiting factors in acid soils are: toxicities of H, Al, and Mn; deficiencies of N, P, K, Ca, Mg, Mo, and Zn; and reduced activity of beneficial microorganisms (Fageria et al., 1989, 1990a). Soil acidity constraints in crop production are very complex, and sometimes it is difficult to separate one constraint from another. Therefore, we assume that three important factors limit plant growth in acid soil: deficiency of nutrients, toxicity of aluminum, and low activities of beneficial microorganisms. These acidity-related constraints are described in this section.

5.3.2.2.1 Phosphorus Deficiency

Phosphorus deficiency is a major limitation to crop production in acidic, infertile soils. Sanchez and Salinas (1981) estimated that P deficiency was a constraint to plant growth for more than 96% of the total area of acid soils in tropical America (23°N–23°S). Sanchez (1987) estimated that P deficiency was a constraint for more than 90% of the total land area of the Amazon Basin. Fageria (1994) studied responses of five crop species to N, P, and K in an Oxisol of central Brazil (Figure 5.6). Results of this study suggested that P was the most yield-limiting nutrient in this acid soil. The two major reasons for the occurrence of P deficiency in acid soils are low native soil P content and high P-fixation capacity. The P-fixation capacity of an Oxisol from central Brazil was studied over a period of 80 days by Fageria and Barbosa Filho (1987), and the amount of P fixed (not recovered by Mehlich-1 extractant) increased from 45 to 268 kg P ha^{-1} when the P application rate was increased from 50 to 400 kg P ha^{-1} high P-fixation capacity is related to clay and Fe and Al contents of these soils (Van Riemsdijk et al., 1984). To obtain good yields, sufficient P fertilization is a prerequisite in these soils (Fageria et al., 1990a; Fageria and Baligar, 2008).

5.3.2.2.2 Aluminum Toxicity

Aluminum is not an essential element for plant growth; however, soluble Al has long been known to be deleterious to plant growth in acid soils (Chaudhary et al., 1987; Fageria and Baligar, 2008).

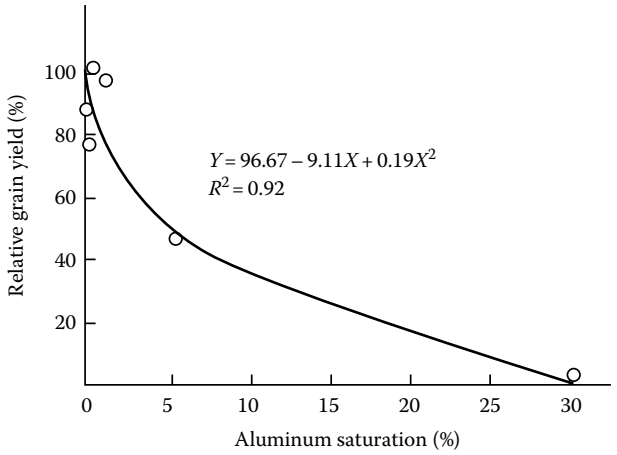

FIGURE 5.8 Relationship between aluminum saturation and common bean grain yield in a "Varzea" soil of Goias State of Brazil.

The interaction between aluminum and various inorganic components in the soil is complex. The soil pH at which aluminum toxicity is expected is therefore ill defined. The initial soil pH at which Al becomes soluble or exchangeable in toxic concentrations depends on many soil factors, including the predominant clay minerals, organic matter levels, concentrations of other cations, anions and total salts, and particularly the plant species or cultivar (Foy, 1984; Fageria et al., 1988a). Generally, aluminum toxicity may be observed at any pH below 5.5, but more commonly it is observed at soil pH below 5.0 (Foy, 1984, 1992). Much of the poor root development and drought stress on soils with strongly acidic (below 5.0) subsoil layers is probably due primarily to Al toxicity that limits both rooting depth and degree of root branching. Aluminum toxicity is a complex disorder that may be manifested as a deficiency of P, Ca, or Mg, or as drought stress (Fageria and Carvalho, 1982; Foy, 1984, 1988; Baligar et al., 1987, 1989; Kamprath and Foy, 1985; Hai et al., 1989). Excess Al has even induced Fe deficiency symptoms in rice, sorghum, and wheat (IRRI, 1974; Clark et al., 1981; Foy and Fleming, 1982). Excess Al in the growth medium influences several physiological and biochemical processes in plants that in turn affect their growth and development.

In general, a more useful predictor of Al toxicity is the percentage of the cation exchange capacity (CEC) occupied by Al (Cregan, 1980; Kamprath and Foy, 1985; Farina and Channon, 1990). To be most effective, the percentage Al saturation must be considered within a rather narrowly defined set of conditions because the critical Al saturation associated with toxicity varies with soil type and with plant species and genotypes (Foy, 1987, 1992).

In Brazil, there are about 35 million ha of lowland areas located near rivers or small natural streams and known locally as Varzeas. These soils have the potential for producing two to three crops per year due to availability of water throughout the year. In the rainy season, these soils are good for flooded rice cultivation, and in the dry season, other crops can be planted provided there is adequate drainage. Aluminum toxicity is one of the important chemical constraints to crop production in Varzea soils (Fageria et al., 1994; Fageria, 2009). Figure 5.8 shows the relationship between Al saturation in Varzea soil of Brazil and relative grain yield of common bean.

5.3.2.2.3 Manganese Toxicity

Manganese toxicity is another important plant growth-limiting factor in acid soils. Unlike Al, Mn seems to affect plant tops more directly than roots, but root damage follows when the toxicity is severe (Fageria et al., 1988a). The solubility and potential toxicity of Mn to a given crop depend upon many soil properties, including total Mn content, pH, organic matter content, aeration, and microbial activity (Foy, 1992). There is a strong antagonism between Fe and Mn.

Iron-deficient snap bean grown in nutrient solution absorbed excess Mn and developed toxicity symptoms (Fleming, 1989). In Brazilian Oxisols, excess Mn creates Fe deficiency in upland rice (Fageria et al., 1990b). However, Wright et al. (1987) found no evidence of Mn toxicity in snap beans grown in 55 horizons from 14 acidic Appalachian soils from the United States. Growth was most closely related to Al/Ca ratios in soil solutions, and Wright et al. (1989) concluded that Mn toxicity was not the major limiting factor in the growth of subclover and switchgrass on acid soils in West Virginia.

5.3.2.2.4 Adverse Effects on Beneficial Microorganisms

The growth of beneficial microorganisms is affected by the pH of the environment. Soil pH is an important factor in determining the amounts and activities of microorganisms involved in organic matter transformations (Alexander, 1980). By regulating microbial activity, pH affects the mineralization of organic matter and the subsequent availabilities of N, P, S, and micronutrients to higher plants (Kamprath and Foy, 1985). In general, organic matter, whether natural or added, decomposes more rapidly in neutral soils than in acid soils. In some strongly acid soils, Al toxicity as well as H^+ ion toxicity may limit microbial breakdown of organic matter.

Inhibited growth of legumes that depend on rhizobial N_2 fixation can be attributed to a direct effect of soil acidity on the growth of the host plant itself (Munns et al., 1981; Jarvis and Robson, 1983), to effects on establishment of the legume–*Rhizobium* symbiosis, or to inhibition of nodule development and/or function (Franco and Munns, 1982). Schubert et al. (1990) reported that at low pH (pH 4.7 and 5.4), dry matter production, seed yield, and N_2 fixation of broad bean were significantly lower than at the higher pH levels (pH 6.2 and 7.0). Buerkert et al. (1990) also reported that in common bean, liming resulted in 40% greater shoot and 18% greater root dry weight, and also improved nodule weight per plant by 110% at early flowering. According to Glenn and Dilworth (1991), *Rhizobium* and *Bradyrhizobium* grow best at around pH 6.5–7.

5.3.2.2.5 Management of Soil Acidity

Soil acidity is a combination of soil conditions that limit plant growth, and its management requires manipulation of various soil and plant factors in favor of better plant growth or crop production. These management practices may vary with severity of acidity, type of soil, type of farming practices, and socioeconomic conditions of the farmer. However, the important soil acidity constraints discussed earlier can be improved in favor of better plant growth by adopting appropriate management strategies. An example of successful soil acidity management can be found in the "Cerrado," an acid Savanna ecoregion of Brazil considered unsuitable for agricultural crop production as recently as the 1970s. The Cerrado covers 205 million ha, of which 175 million ha are in central Brazil. Approximately 112 million ha of the Cerrado are considered adequate for developing sustainable agricultural production in central Brazil (Schaffert, 1993). The soils of the Cerrado are commonly characterized by low pH, low phosphorus availability, low fertility, and toxicity of Al and Mn (Goedert, 1983; Fageria and Baligar, 2008). Today 12 million ha of the Brazilian Cerrado are in crop production, producing 25% of Brazil's rice, maize, and soybean, 20% of its coffee, and 15% of its common beans. Another 35 million ha of improved pastures have been developed in the Cerrado, carrying 53 million head of cattle and producing 40% of Brazil's meat and 12% of its milk (Schaffert, 1993). All of this progress has been achieved by the adoption of acid soil management strategies. These are discussed in the following section.

5.3.2.2.5.1 Improving P-Use Efficiency Various management practices can be used to improve P-use efficiency in P-deficient soils. An important practice is band application of P based on soil conditions and the cropping system. Field trials in combination with soil tests for available phosphorus are required to recommend fertilizer P requirements for representative soil types, crops, and climatic conditions (Mengel, 1993). Phosphorus use efficiency depends on soil structure, since a good structure favors root growth and thus the capacity of plant roots to exploit soil

phosphate. In this situation, adequate phosphorus fertilization is an important cultural practice to improve soil structure. Moreover, phosphorus deficiency in high P-sorbing soils can be corrected by an initial application of a large quantity of P, or a combination of an initial broadcast application and repeated band applications (Yost et al., 1979). Liming is another practice to improve P uptake by plants in acid soils through precipitation of Fe and Al hydroxides up to a pH of about 6.5 (Fageria, 1984, 1992; Fageria and Baligar, 2008). Fageria (1984) also reported that in Brazilian Oxisols, there was a quadratic increase in the Mehlich 1 extractable P in the pH range of 5–6.5, and thereafter, it was decreased. The increase of available P in the pH range of 5–6.5 was associated with release of P ions from Al and Fe oxides, which were responsible for P fixation (Fageria, 1989). At higher pH (>6.5), the reduction of extractable P was associated with fixation by Ca ions. This increase in extractable P as pH increases from 5 to 6.5 and the reduction in extractable P in the higher pH range (>6.5) can be explained with the help of following equations (Fageria and Baligar, 2008):

$$AlPO_4(\text{P fixed}) + 3OH^- \leftrightarrow Al(OH)_3 + PO_4^{3-}(\text{P released})$$

$$Ca(H_2PO_4)_2(\text{soluble P}) + 2Ca^{2+} \leftrightarrow Ca_3(PO_4)_2(\text{insoluble P}) + 4H^+$$

Liming acid soils results in the release of P for plant uptake. This effect is often referred to as "P spring effect" of lime (Bolan et al., 2003). Bolan et al. (2003) reported that in soils high in exchangeable and soluble Al, liming may increase plant P uptake by decreasing Al, rather than by increasing P availability per se. This may be due to improved root growth where Al toxicity is alleviated, allowing a greater volume of soil to be explored (Friesen et al., 1980). Beyond that pH, fixation of P occurs through formation of calcium phosphate. Addition of organic manures and inoculation with mycorrhizal fungi are additional management strategies to improve P-use efficiency in P-deficient acid soils. All these practices are related to modification of the soil environment. However, farmers are often unable to afford costly phosphorus fertilizers, especially in developing countries where a large percentage of the world's acid soils are located.

An integrated fertilization–plant breeding approach seems likely to give more economically viable and practical results in the future. Exploiting genotypic differences in absorption and utilization of P to improve efficiency of fertilizer P uptake and obtain higher productivity on P-deficient soils has received considerable attention in recent years (Fageria et al., 1988b; Baligar et al., 1990; Clark, 1990). Fageria (1994) studied differences among crop species in relation to decrease in dry weights of tops under P stress and adequate supply of P in an acid soil of Brazil. Susceptibility to P deficiency among crop species was: rice > corn > common bean > wheat > soybean. That is, among the five crop species, rice was most sensitive to P deficiency, and soybean was least sensitive. Plant species differ in their ability to acquire soil P (Hanway and Olson, 1981) due to differences in root morphology (Barley, 1970), uptake characteristics (Fohse et al., 1991), mycorrhizal associations (Bolan, 1991), and the effect of the plant root on soil chemistry and P solubility (Ibrikci et al., 1994).

Many studies have shown that plants display a wide array of adaptive responses to low P availability (Faye et al., 2006; Fageria and Baligar, 2008). A well-known adaptive response is the alteration of root morphology and architecture to increase P acquisition from the soil at minimum metabolic cost (Neumann et al., 1999; Jonathan and Kathleen, 2001; Yong et al., 2003). In this regard, morphological and genotypic variations are well documented for many plants, such as barley (Gorny and Patyna, 1984), corn (Aina and Fapohunda, 1986), rice and dry bean (Fageria, 2009), and pearl millet (Faye et al., 2006). Faye et al. (2006) reported that pearl millet adaptation to low water and soil P availability has been related to root properties.

Increased fertilizer P uptake efficiency has been noted when P has been applied with N fertilizers. The effect of added N may be physiological enhancement of P uptake with added NH_4, enhanced P uptake when applied in a band with N, or NH_4-induced acidification near the root, and an increase in the concentration of $H_2PO_4^-$ compared with HPO_4^{2-} (Riley and Barber, 1971; Miller et al., 1990). A decrease in precipitation of fertilizer P when banded with $(NH_4)_2SO_4$ was attributed to NH_4-induced acidification (Miller et al., 1970). Fan and Mackenzie (1994) reported that total N and P uptake by corn was increased by banding urea with triple superphosphate or monoammonium phosphate, and fertilizer P-use efficiency increased from 40% to 80%.

Addition of organic matter can also improve P uptake. In addition to providing a reservoir of organic P, dissolved organic matter could increase the availability of P (Chien et al., 1987) and reduce P fixation (Mikeni and Mackenzie, 1987).

Colonization of crop roots by arbuscular mycorrhizal fungi (AMF) can enhance P uptake in crops by increasing the effective zone of exploration around the roots and accessing P unavailable to nonmycorrhizal roots (Hayman, 1983; Bittman et al., 2006). Colonization by AMF is particularly important for juvenile corn plants when root access to soil P lags behind overall plant demand (Miller, 2000). However, colonization of corn roots is diminished by high P status in soil (Fries et al., 1998) and plants (Lu et al., 1994). In addition, application of small amounts of P fertilizer near the seed (starter P) improves production of corn, particularly on low-P soils (Lauzon and Miller, 1997). Bittman et al. (2006) also reported that starter P improves early growth of corn even on a soil of relatively high soil-test P receiving a large amount of P as broadcast liquid dairy manure or fertilizer.

5.3.2.2.5.2 Liming The most common and, in most cases, the most effective way to correct soil acidity is by applying lime. Liming is the practice of adding liming materials to acid soils for the purpose of increasing soil pH and maintaining a favorable soil environment for plant growth. A more favorable root environment may be a consequence of the following effects:

1. Desirable soil pH
2. Decreasing the toxicity of Al and Mn
3. Increasing Ca and Mg supplies
4. Enhancing the availability of P and Mo
5. Improving mineralization of organic compounds, thereby improving N, S, and P uptake
6. Improving soil biological activity, such as nitrogen fixation

The quantity of lime added depends on type of soil, liming material, crop species, cultivar, and economic considerations. The formula to compute soil lime requirements is given by Fageria and Baligar (2008). In addition, Cochrane et al. (1980) also developed the following equation for liming acid mineral soils to compensate crop aluminum tolerance while accounting for the levels of exchangeable Ca and Mg in the soil:

$$\text{Lime required}\,(CaCO_3, \text{equiv. t ha}^{-1}) = 1.8\left[\frac{\text{Al} - \text{CAS(ECEC)}}{100}\right]$$

where CAS = critical aluminum saturation or required aluminum saturation of the effective cation exchange capacity (ECEC)

$$\text{Al Sat} = \left[\frac{\text{Al}}{\text{ECEC}}\right] \times 100$$

where ECEC is the sum of exchangeable Al, Ca, Mg, and K in cmol kg^{-1} of soil in 1 M KCl extractant at original soil pH.

TABLE 5.2
Critical Al Saturation for Important Field Crops at 90%–95% of Maximum Yield

Crop	Type of Soil	Critical Al Saturation (%)	Reference
Cassava	Oxisol/Ultisol	80	Howeler (1991)
Upland rice	Oxisol/Ultisol	70	Wade et al. (1989)
Cowpea	Oxisol/Ultisol	55	Wade et al. (1989)
Cowpea	Oxisol	42	Smyth and Cravo (1991)
Peanut	Oxisol/Ultisol	65	Foster et al. (1980)
Peanut	Xanthic Hapludox	54	Smyth and Cravo (1992)
Soybean	Oxisol	19	Smyth and Cravo (1991)
Soybean	Xanthic Hapludox	27	Smyth and Cravo (1992)
Soybean	Oxisol/Ultisol	15	Wade et al. (1989)
Soybean	Not given	<20	Kamprath (1970)
Soybean	Ultisol	20–25	Sartain and Kamprath (1975)
Soybean	Histosol	10	Mengel and Kamprath (1978)
Soybean	Ultisol	20	Pearson et al. (1977)
Corn	Oxisol	19	Smyth and Cravo (1991)
Corn	Xanthic	27	Smyth and Cravo (1992)
Corn	Oxisol/Ultisol	29	Wade et al. (1989)
Corn	Oxisol/Ultisol	25	Foster et al. (1980)
Corn	Oxisol	28	Sanchez (1976)
Mung bean	Oxisol/Ultisol	15	Foster et al. (1980)
Mung bean	Oxisol	5	Wade et al. (1989)
Coffee	Oxisol	60	Sanchez (1976)
Sorghum	Oxisol	20	Sanchez (1976)
Common bean	Oxisol	10	Howeler (1991)
Common bean	Oxisol	8–10	Abruna et al. (1975)
Common bean	Oxisol	23	Salinas and Sanchez (1977)
Cotton	Not given	<10	Kamprath (1970)

For most agronomic crops, Al^{3+} concentration or activity in the soil solution or Al saturation in the exchange complex appears to be the best single measure to assess potential Al toxicity for a given soil (Kamprath, 1971). When Al saturation of exchange capacity exceeds 60%, appreciable amounts of Al^{3+} dissolve in the soil solution (Nye et al., 1961). At this point, Al toxicity, caused by soil acidity, can occur. Table 5.2 shows critical Al saturation for important field crops. Heavy fertilization could induce Al toxicity even in soils with a relatively low Al saturation (Kamprath, 1970, 1971). Intensive cropping and use of acid-forming fertilizers without proper liming will aggravate the situation (Beverly and Anderson, 1987).

Use of gypsum ($CaSO_4 \cdot 2H_2O$) or phosphogypsum is another management strategy to reduce soil acidity. Phosphogypsum is a by-product of wet acid production of phosphoric acid from rock phosphate. It is essentially hydrated $CaSO_4$ with small proportions of P, F, Si, Fe, Al, several minor elements, heavy metals, and radionuclides as impurities (Alcordo and Recheigl, 1993). Worldwide production of phosphoric acid, estimated at 11 million Mg of P annually (Lin et al., 1990), also results in the production of approximately 125 million Mg of phosphogypsum. With only about 4% of the world's phosphogypsum production being used in agriculture and in gypsumboard and cement industries, about 120 million Mg of phosphogypsum accumulates annually. Most of this excess is stockpiled, and some is stored in abandoned quarries or, in certain countries, dumped into waterways (Alcordo and Recheigl, 1993).

Field calibration data would provide the best approach for recommending gypsum for field crops. However, Malavolta (1991) proposed the following equations to apply gypsum for field crops in Cerrado soils of Brazil (mostly Oxisols and Ultisols):

$$\text{Rate of gypsum (Mg ha}^{-1}) = (0.4 \times \text{ECEC} - \text{Ca}) \times 2.5 \quad \text{or}$$

$$\text{Rate of gypsum (Mg ha}^{-1}) = (\text{Al} - 0.2 \times \text{ECEC}) \times 2.5$$

where values of ECEC and Al should be expressed in cmol kg^{-1} of soil. In a much simpler approach, Souza (1988) suggested that for highly weathered Oxisols, such as the soils of the Cerrado, gypsum rates should be based on clay content. He proposed 0.5, 1.0, 1.5, and 2.0 Mg ha^{-1} gypsum for soils of sandy texture, medium texture, clayey texture, and very clayey texture, respectively.

For the management of Al toxicity with the use of lime or gypsum materials, the Ca–Al balance index of Noble et al. (1988) should be helpful. Most of the studies showed that surface-applied gypsum or phosphogypsum ameliorated subsoil Al toxicity, acidity, and infertility in shorter time periods than surface-applied liming materials (Alcordo and Recheigl, 1993). In addition, phosphogypsum is a good source of S and Ca for crops.

5.3.2.2.5.3 Use of Tolerant Species and/or Cultivars In addition to liming and gypsum application, use of Al- and Mn-tolerant crop species and cultivars can be a complementary solution for crop production on acid soils. Aluminum tolerance of some important crop species is presented in Figure 5.9. Among six crop species, rice is most tolerant to Al toxicity, and mung bean is most sensitive. Other acid-tolerant crop species are cassava, potato, millet, and pigeon pea. Differences among cultivars of important food crops have been widely reported for Ca and Mg deficiencies and Mn toxicities (Foy, 1984; Kamprath and Foy, 1985; Fageria et al., 1989; Fageria and Baligar, 2008; Fageria, 2009). Table 5.2 shows critical Al saturation of various crop species.

In addition to the above management practices, acid soils amended with large quantities of organic residues give low Al^{3+} concentrations in soil solution and permit good growth of crops under conditions where toxicities would otherwise occur. Deep tillage to lower the concentration of toxic elements in the surface soil and selection of plants with deep rooting characteristics are additional methods to enhance crop production on acid soils.

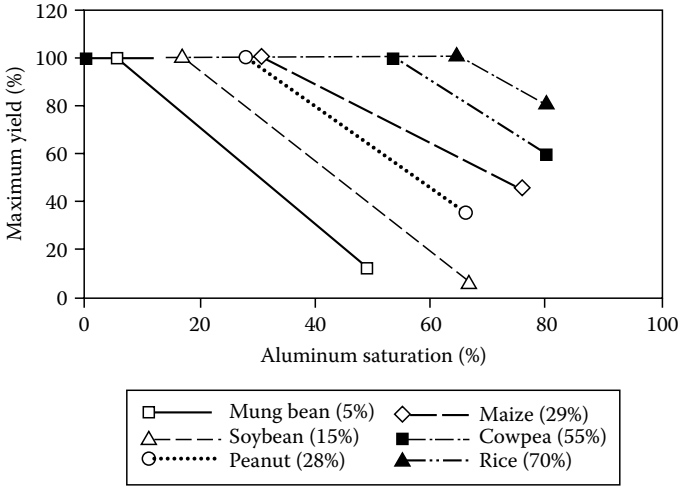

FIGURE 5.9 Aluminum tolerance of crop species. (From Wade, M.K. et al., Overcoming soil fertility constraints in a transmigration area of Indonesia, Tropsoils Bull. 88-01, North Carolina State University, Raleigh, NC, 1989.)

5.3.2.3 Saline-Sodic Soils

Soil salinity is a major environmental constraint to crop productivity worldwide (Ashraf and Foolad, 2005). It is estimated that approximately 20% of cultivated lands and 33% of irrigated agricultural lands in the world are affected by excessive salinity (Tanji, 1990; Francois and Maas, 1994; Ashraf and Foolad, 2005). Furthermore, salinized areas are increasing at a rate of 10% annually (Kalaji and Pietkiewica, 1993). Many soils have been adversely modified for growth of most crop plants by the presence of high soluble salts or exchangeable sodium, or both. A saline-sodic soil has saturation extract conductivity more than 2 dS m^{-1} at 25°C and exchangeable sodium percentages of more than 15. The pH of such soil is less than 8.5. Salt-affected soils are distributed worldwide. The total area of these degraded soils is about 0.9 billion ha (Lal et al., 1989). The global distribution of saline soils is about 0.34 billion ha and of sodic soils is about 0.56 billion ha. Salt-affected soils are common in arid and semiarid regions where evaporation is higher than precipitation. As a result, salts are not leached from the soil and accumulate in amounts and types detrimental to plant growth. Soil salinization also occurs in irrigated lands. The traditional practice of flood irrigation with large volume of water causes much percolation through the soil, which tends to raise watertables, to saturate the soil excessively, (known as waterlogging) and to accumulate salts at or near the soil surface (Hillel, 1998). Soils are also salinized in coastal areas due to tides. Salts generally originate from native soil and irrigation water. Use of inappropriate levels of fertilizers with inadequate management practices can create saline conditions even in humid regions.

Sodic soils (which have an Na absorption ratio greater than 15 in saturation extracts) form when annual fluctuations in soil water conditions cause two opposing processes: Na concentration and dissipation (Seelig and Richardson, 1994). For example, lateral subsurface flow and annual fluctuation of a shallow watertable created an area of sodic soils in Alberta, Canada (Fullerton and Pawluk, 1987). Sodic soils typically occur on landscape positions with high evaporative discharge that concentrates Na salts near the soil surface. Evaporative discharge is defined as a loss of water from groundwater to atmosphere by evapotranspiration (Seelig and Richardson, 1994).

Reduced productivity occurs as a result of decreased yields on land that is presently cultivated. About one-third of all irrigated land is considered to be affected by salt (Epstein et al., 1980). Salt problems also restrict significant agricultural expansion into areas that presently are not cultivated. In the United States, salinity is a major limiting factor to agricultural productivity, and as the quality of irrigation water continues to decline, this problem will become more acute.

5.3.2.3.1 Salinity Management Strategies

Successful crop production on salt-affected soils depends on soil, water, and plant management. Technological approaches to cope with salinity and sodicity include water and soil management, irrigation methodology, and perhaps desalinization. Saline-sodic soils can be reclaimed by providing a source of Ca^{2+}, such as gypsum, to replace Na^{+} from cation exchange sites, a process that requires the flow of water through the soil (Ilyas et al., 1993). The cost of soil reclamation is frequently so high that it is not possible to reclaim such soils for crop production. Under these circumstances, biological approaches include the identification of halophytes that are potential crop plants and, if necessary, the introduction of more desirable horticultural or agronomic traits into them, the introduction of salt-tolerance characteristics into crop plants, the majority of which are glycophytic, or the manipulation of glycophytic crop plants to adjust and produce under conditions of moderate or low levels of salinity (Hasegawa et al., 1986). Table 5.3 shows differences in crop species in relation to salinity tolerance. With recent developments in biotechnology, there is also potential for obtaining salt-tolerant crop genotypes by the use of somatic cell selection or protoplast fusion methodologies or by gene transformation using recombinant DNA methodologies (Hasegawa et al., 1986). Although such approaches have contributed significantly to our understanding of the genetic controls of salt tolerance at the molecular and cellular levels, thus far only limited progress has been made in developing transgenic plants with improved salt tolerance (Ashraf and Foolad, 2005). This is, in part, due to the fact that plant response to salinity is different at different levels of

TABLE 5.3
Relative Tolerance of Important Field Crops to Salinity

Tolerant	Moderately Tolerant	Moderately Sensitive	Sensitive
Barley	Sorghum	Corn	Rice
Cotton	Wheat	Peanut	Sesame
Oats	Pearl millet	Chickpea	Blackgram
Rye	Soybean	Sugarcane	Pigeon pea
Triticale	Sunflower	Alfalfa	Common bean
Sugar beet	Cowpea	Broad bean	Mung bean
Guar	Winged bean	Ladino clover	Carrot
Canola or rapeseed		Common vetch	Onion
		Cassava	
		Eggplant	
		Garlic	
		Pea	
		Pepper	
		Potato	
		Radish	
		Sweet potato	
		Tepary bean	
		Tomato	

Source: Compiled from Maas, E.V., Testing crops for salinity tolerance, in *Proceedings of a Workshop on Adaptation of Plants to Soil Stresses*, INTSORMIL (ed.), University Nebraska-Lincoln, Lincoln, NE, 234–247, August 1–4, 1993.

organization, including cell, tissue, organ, and whole plant, and also that, at each level, different sets of genes might be involved (Ashraf, 2002; Quesada et al., 2002; Ashraf and Foolad, 2005).

5.3.2.4 Allelopathy

Allelopathy, the direct or indirect effect of one plant on another through the production of chemical compounds that escape into the environment (Rice, 1974, 1979; Smith and Martin, 1994), occurs widely in natural plant communities and is postulated to be one mechanism by which soil degradation occurs. Originally, allelopathy was defined as the biochemical interactions between plants of all kinds including the microorganisms that are typically placed in the plant kingdom (Fageria and Baligar, 2003). Since then, the term has undergone several changes and is now defined as any "direct or indirect harmful or beneficial effect by one plant on another through the production of chemical compounds that escape into the environment" (Rice, 1984). Actual and potential roles of allelopathy in agriculture have been extensively reviewed (Rice, 1974, 1979; Putnam and Duke, 1978; Smith, 1991; Fageria and Baligar, 2003; Fageria et al., 2008). In general, allelopathy has been related to problems with crop production on certain types of soil, with stubble mulch farming, with certain types of crop rotations, with crop monoculture, and with forest site replanting (Putnam and Duke, 1978). Some chemical compounds implicated as effective allelopathic agents include simple phenolic acids, coumarins, terpenoids, flavonoids, alkaloids, cyanogenic glycosides, and glucosinolates. It is also reported in the literature that secondary compounds implicated in biochemical interactions among plants also have been reported to be involved in several protective or defensive functions for the plant (Putnam and Duke, 1978). Release of these chemical compounds into the environment occurs by oxidation of volatile chemicals from living plant parts, by leaching of water-soluble toxins from aboveground parts in response to the action of rain, fog, or dew, by exudation of water-soluble toxins from below-ground parts, or by release of toxins from nonliving plant parts through leaching

of toxins from litter, sloughed root cells, or as microbial by-products resulting from litter decomposition. Once these chemicals are released into the immediate environment, they must accumulate in sufficient quantity to affect other plants, persist for some period, or be constantly released in order to have lasting effects (Putnam and Duke, 1978).

Brazil is the largest producer of upland rice in the world. Upland rice is grown in central Brazil (a tropical savanna, called "Cerrado" that covers 23% of the country). Most of the soils are Oxisols, poor in fertility and high P immobilization capacity (Fageria and Baligar, 2001, 2008). Upland rice yield on Oxisols decreased significantly when grown in monoculture for more than 3 years (Fageria and Baligar, 2003; Fageria et al., 2008). Allelopathy is assumed to be one of the main reasons for decreasing upland rice yield in monoculture (Fageria and Baligar, 2003). Olofsdotter et al. (1995) reported that majority of Brazilian upland rice germplasm was allelopathic. Experiments with rice in Philippines have shown that residual effects of allelochemicals reduced the yields of subsequent rice crops (Olofsdotter et al., 1995). Chou (1980) reported 25% reduction in rice yield of second crop in Taiwan, and such reduction was attributed to the phytotoxins produced during the decomposition of rice residues left on the soil. This review aims to discuss allelopathy-related problems in upland rice in Brazil and suggesting appropriate management practices to overcome them.

5.3.2.4.1 Minimizing Allelochemical Effects

Allelochemical effects can be reduced by adopting certain management practices. Among these practices are use of appropriate crop rotations, improving organic matter content of the soil, leaving cropped areas fallow for certain periods of time to allow decomposition of allelochemicals, and planting resistant cultivars or plant species. The use of companion plants that contribute organic matter or inoculation with microorganisms that can readily metabolize the toxins might prove useful in perennial crop ecosystems (Putnam and Duke, 1978).

Use of land for pasture is an important practice to restore land degraded by allelochemicals produced by upland rice. Experiments conducted at the National Rice and Bean Research Center of EMBRAPA, Brazil showed that land degraded by upland rice allelochemicals (yield less than 1000 kg ha^{-1}) can be restored to normal rice yield (>4000 kg ha^{-1}) by leaving land under pasture (brachiaria grass) for 4 years followed by planting soybean during the rainy season and irrigated dry beans during the dry season.

Pasture improves soil quality through increasing the organic matter content of the soil by pasture crops (Schnabel et al., 2001; Skinner et al., 2004, 2006). Distribution of SOC within the soil profile is a function of plant functional types with shoot versus root allocation and vertical root distribution affecting the distribution of SOC with depth (Jobbagy and Jackson, 2000). In addition, a large proportion of nutrients ingested by animals is returned to the soil in the urine and feces (Fageria et al., 2008). Animals retain only a small proportion, about 20%, of the nutrient they ingest, and the rest is returned to the soil through excreta (Rao et al., 1992). The expected buildup in soil fertility in a grazed grass–legume pasture could result from a more rapid cycling of organic nutrients and a greater proportion of nutrients in a plant available form. Appropriate management of pastureland improves soil biological activity and reduces soil erosion. The increased biological activity is beneficial to the soil properties such as mineralization, humification, texture, porosity, water infiltration, and retention (Fageria et al., 2008).

5.3.2.5 Indiscriminate Use of Pesticides

Indiscriminate use of pesticides such as insecticides, fungicides, and herbicides has adverse effects on soil biology. Changes in the soil microflora may have significant effects on soil productivity and sustainability. Excessive use of pesticides may also pollute groundwater. Although the application of agricultural chemicals has greatly increased the productivity of modern agriculture, deleterious effects of these chemicals on soil biology and water quality have been reported (Li and Ghodrati, 1994). Many agricultural chemicals have been detected in groundwater in many areas of the United States (Holden, 1986). Extensive groundwater monitoring and experimental data, however, show that preferential flow is likely

to be one of the principal mechanisms responsible for accelerated movement of these chemicals in many field soils (Ellsworth et al., 1991). Preferential flow refers to any transport process through which water and solutes gain enhanced movement (Luxmoore, 1991). The rise of soil degradation due to excessive use of pesticides can be avoided by advising farmers to rationally use these materials based on experimental evidence for each agroecological region.

5.3.3 Biological Degradation

Biological degradation refers to the loss of organic matter, reduction in biomass carbon, and decline in the biotic activity of soil fauna (Lal, 1989). Biological degradation factors also include infestation of crop plants with diseases, insects, and weeds that reduce crop growth and yield.

5.3.3.1 Decrease in Soil Organic Matter Content

Soil organic matter is composed of a series of fractions from very active to passive (Schimel et al., 1989). These fractions have been conceptualized in mathematical models as kinetically defined pools with different turnover rates (Van Veen et al., 1984; Parton et al., 1987). Stable organic matter usually has a C/N ratio between 10 and 17 (Stevenson, 1986; Vaughan and Ord, 1991). The C stored in soils is nearly three times that in the aboveground biomass and approximately double that in the atmosphere (Eswaran et al., 1993a).

The literature on soil organic matter is replete with references to the positive effects of this component on soil chemical, physical, and biological properties that, in turn, contribute to improved crop yields (Stevenson, 1982a,b; Bauer and Black, 1994). As a chemical reservoir, there is universal acknowledgment that soil organic matter is the main indigenous source of soil available N and that it contains as much as 65% of the total soil P and provides significant amounts of sulfur and other nutrients essential for plant growth. It is also universally accepted that the C fraction is used by soil microorganisms as a major energy source for metabolic activity, in the process altering nutrient availability and soil structure (Paul, 1991). Because organic matter affects soil structure, soil physical properties can be altered by increasing or decreasing soil organic matter (Bauer and Black, 1994). According to Bauer and Black (1994), the contribution of 1 Mg organic matter ha^{-1} to soil productivity, across the range of 64–142 Mg organic matter ha^{-1}, was calculated as equivalent to 35.2 kg ha^{-1} for spring wheat total dry matter and 15.6 kg ha^{-1} for grain yield. Loss of productivity associated with depletion of soil organic matter in the Northern Great Plains of the United States is primarily a consequence of a concomitant loss of fertility (Bauer and Black, 1994). Soil erosion in the Northern Great Plains is deemed to diminish soil productivity through loss of soil organic matter. According to Bauer and Black (1994), the contribution to productivity of a unit quantity of soil organic matter is the quotient of the difference in the crop yield grown on sites differing in soil organic matter content and the difference in the soil organic matter content of these sites in the plow layer.

Kaolinitic soils of temperate as well as tropical regions are characterized by high dispersibility, a factor that may increase the susceptibility of cultivated soils to aggregate disruption, surface crusting, reduced infiltration, and erosion (Sumner, 1992). In warm, humid climate regions, these factors can contribute to a rapid loss of soil organic matter under cultivation and a decline in the productivity of agricultural soils (Bruce et al., 1990).

Long-term cultivation alters soil structure and increases losses of soil organic matter (Dalal and Mayer, 1986; Lal, 2003). By mineralization, leaching, erosion, or change in the land use, 50%–70% of the antecedent SOC can be lost as CO_2 over several decades (Lorenz and Lal, 2005). Apart from soil type and climate variables, the magnitude of these effects depends on the intensity of cultivation, in particular the type and frequency of tillage and the quantity and quality of fertilizers and organic residues returned to the soil (Rasmussen and Collins, 1991). Elliott (1986) and Gupta and Germida (1988) attributed much of the soil organic matter lost during cultivation of grassland soils to mineralization of soil organic matter binding microaggregates into

macroaggregates. Macroaggregates are much less stable than microaggregates (Oades, 1984; Beare et al., 1994a), probably because of the nature of the binding agents involved. Macroaggregates are also more susceptible to the disruptive forces of cultivation and to the dispersion that results from rapid wetting or raindrop impact (Tisdall and Oades, 1982).

The decomposition rate of soil organic matter is doubled for every 10°C increase in mean temperature. The climate index used by FAO to assess loss of organic matter is (Lal, 1989):

$$K = \frac{1}{12}\, 0.1065t \times \frac{P}{\text{PET}} \quad \text{(with } P \text{ less than PET)}$$

where

t is mean air temperature during the month
P is precipitation
PET is potential evapotranspiration
K is rate of humus decay in percent per year

If P is greater than PET, P divided by PET = 1, and if t is less than 0, $t = 0$.

5.3.3.1.1 Management Strategies

Agricultural management practices influence the amount of organic matter present in soils and cause changes in the rate of soil organic matter turnover (Cambardella and Elliott, 1994). Because soil organic matter is composed of a series of fractions, management practices will also influence the distribution of organic C and N among soil organic matter pools. Cultivation of soils results in the disruption of soil aggregates and the loss of soil organic matter compared with native sod and pasture soils (Elliott, 1986; Kay, 1990). Therefore, one strategy for improving soil organic matter content is to include fallowing or pasture in the farming system. Little inorganic N is accumulated in a prairie or in a grassland ecosystem, and thus little is lost to either leaching or denitrification (Goodroad and Keeney, 1984). Although inorganic N is continuously mineralized from soil organic matter, it rarely accumulates in a grassland soil due to rapid immobilization by microbial activity (Woodmansee et al., 1981; Jackson et al., 1989). Conservation tillage is another practice to improve soil organic matter content of cultivated land. With no-tillage management, the soil is not plowed, and crop residues accumulate on the soil surface as a mulch. Several studies have shown that if residues are not removed, no-tillage or minimum tillage can improve soil aggregation and reduce losses of soil organic matter that result from cultivation (Havlin et al., 1990; Carter, 1992; Beare et al., 1994b). Conventional tillage practices disrupt soil aggregates, exposing more organic matter to microbial attack. Organic matter may be protected from microbial attack by adsorption to clay minerals (Oades, 1984; Ladd et al., 1985) and the formation of microaggregates (Gregorich et al., 1989), by isolation in micropores (Foster, 1981), and by physical protection within stable macroaggregates (Elliott, 1986; Gupta and Germida, 1988).

According to Beare et al. (1994b), macroaggregates in no-tillage soils provide an important mechanism for the protection of soil organic matter that may otherwise be mineralized under conventional tillage. Soil organic matter is enriched by return of crop residues, growing green manures, and application of farmyard manures and other materials containing organic substances (e.g., peat and humic materials). Simultaneous additions of organic materials and N fertilizers can increase total soil organic matter content (Stevenson, 1986). The result of long-term additions of organic materials to soil is increased soil organic matter, crop productivity, and soil biological activity (Collins et al., 1992). Livestock manure has been used as a soil amendment in agricultural systems for centuries (McAndrews et al., 2006). The application of livestock manure to degraded soil increases soil organic matter providing several potential benefits including improving soil fertility, structure, and water holding capacity (Clark et al., 1998; Grandy et al., 2002; McAndrews et al., 2006). Butler and Muir (2006) reported that use of composted dairy manure promotes soil aggregation, which

improves soil structure, increases soil pH, benefits water infiltration rate, and improves water holding capacity. The N, P, and K percentages of dairy compost are relatively low, but the benefits of manure lie in the slow release of organically bound N and P in the soil that plants can use effectively (Gershuny and Martin, 1992).

High rates of animal manures can sustain crop yields (Bouldin et al., 1984). However, studies utilizing typical farm scale management practices have shown that replacement of inorganic N with organic (animal or green manure) N sources resulted in unacceptable yield reduction related to N availability during the first few years of transition (Doran et al., 1987). A successful transition from inorganic to organic N sources, therefore, can be achieved by adding a small amount of inorganic fertilizer to supplement the manures. Grassland soils tend to lose from 30% to 50% of their original soil organic matter in the first 40–50 years of cultivation (Tiessen et al., 1982; Mann, 1985). Rapid depletion of the easily mineralizable organic matter is the primary reason for the initial C loss (Bowman et al., 1990). Organic matter changes thereafter largely become a function of soil management and erosion (Rasmussen and Parton, 1994). Use of green manuring, minimum or no-tillage systems, and addition of livestock manures are some specific practices that can be used to increase soil organic matter contents of degraded soils. These practices are discussed under separate headings.

5.3.3.1.1.1 Green Manuring A green manure is a crop used primarily as a soil amendment and a nutrient source for subsequent crops (Cherr et al., 2006a,b). Leguminous green manure may add N to crop systems through biological fixation, and the slow release of N from decomposing green manure residues may be well timed to supply the N requirements of subsequent crops (Cline and Silvernail, 2002; Cherr et al., 2006b). Green manure crops were historically used to supply plant nutrients and organic matter for increasing soil fertility. China has a 3000 year history of using green manures to increase yields of cereal crops and to maintain and increase soil fertility (Lizhi, 1988). As agriculture became more specialized, especially in developed countries, the use of green manures as components of cropping systems was practically eliminated. Research at many experiment stations in the United States and abroad showed that concentrated fertilizer nitrogen could replace legumes and manures as a readily available source of nitrogen for nonlegume crops. The result was a rapid intensification of cropping based on fertilizer nitrogen. In recent years, the high cost of nitrogen fertilizer and water quality problems associated with inappropriate use of nitrogen fertilizers have generated a renewed interest in legume green manures as an alternative source of nitrogen. In addition to fixing nitrogen, legume green manures maintain ground cover, reduce erosion, and provide weed control. They improve soil physical conditions and promote mycorrhizae on the roots of succeeding crops, increasing soil phosphorus availability. They may also suppress plant pests such as nematodes. Studies in Brazil have shown that some legume green manures are very effective in suppressing soybean nematodes, resulting in increased yields (Sharma et al., 1982). Green manures, especially those that have tap roots or root deeply into the soil, may also prevent or help alleviate compaction in intensively cultivated soils (Taylor, 1974). Partial replacement of fallow with legumes would reduce the risk of erosion and nutrient leaching and minimize the hazard of salinization and eutrophication of downstream ecosystems (Biederbeck and Bouman, 1994). When used in place of fallow, well-chosen green manures may reduce erosion (Dapaah and Vyn, 1998), reduce nutrient or pesticide losses (Delgado et al., 2001), and suppress weeds (Dyck et al., 1995; Burgos and Talbert, 1996). Green manures may also offer habitat or resources for beneficial microorganisms and desirable wildlife (Bugg et al., 1991; Nicholls and Altieri, 2001).

A vast array of legume species has potential as green manures. In temperate regions, many legumes are used mainly as forage for livestock. These include alfalfa (*Medicago sativa* L.), several clovers (*Trifolium* spp.), vetch (*Vicia* spp.), and other less familiar species (Lathwell, 1990). Annual dry matter accumulation by these legumes varies from 1 Mg ha^{-1} to more than 10 Mg ha^{-1} under ideal growing conditions. Quantities of N accumulated in the aboveground dry matter range from

20 kg N ha^{-1} to as much as 300 kg N ha^{-1} annually. There are several hundred species of tropical legumes, but only a fraction of these have been studied for their potential as green manures. Some important tropical species used as green manures are *Mucuna* or velvet bean (*Mucuna aterrima*), crotalaria (*Crotalaria striata*), zornia (*Zornia latifolia*), jack bean (*Canavalia ensiformis*), pigeon pea (*Cajanus cajan*), tropical kudzu (*Pueraria phaseoloides*), guar (*Cyamopsis tetragonoloba*), mung bean (*Vigna radiata*), and cowpea (*Vigna unguiculata*).

Mughogho et al. (1982) reported that in Trinidad, cowpeas produced about 3.5 Mg ha^{-1} of dry matter, with about 1.8 Mg ha^{-1} as grain. Grain contained from 45 to 50 kg N ha^{-1}, whereas the residue contained from 15 to 20 kg N ha^{-1}. Results from the International Institute of Tropical Agriculture (IITA) in Nigeria were similar to those found in Trinidad (Eaglesham, 1982). In an experiment at the International Crop Research Institute for the Semiarid Tropics in India, pigeon pea produced 6 Mg ha^{-1} of dry matter, of which 1.6 Mg ha^{-1} was grain (Kumar et al., 1982). Estimated N content was about 40 kg N ha^{-1} in the grain and 50 kg N ha^{-1} in the residue. George et al. (1994) reported that mung bean fixed from 37 to 63 kg N ha^{-1} and *Sesbania rostrata* fixed from 68 to 154 kg N ha^{-1} as green manures in lowland rice cropping systems on Alfisols in the Philippines. There are several desirable characteristics that can contribute to the effective use of green manure crops. Some of these characteristics are (1) short duration, fast growing, and high nutrient accumulation ability; (2) wide ecological adaptability; (3) efficient water use; (4) pest and disease resistance; (5) ease in incorporation; and (6) high N accumulation in underground plant parts. Certainly, green manure crops have some distinct advantages in some climates, on some soils, and in some socioeconomic situations.

It has been widely reported in the literature that beneficial effects of organic manures in restoring soil productivity were much larger than those from inorganic fertilizers (Larney and Janzen, 1996; Fageria et al., 2005; Fageria, 2007). Larney and Janzen (1996) reported that use of organic manures (livestock and crop residues) might provide an alternative for producers with a desire to restore their eroded soils and, at the same time, reduce their inputs of N and P fertilizer. It has been also reported that organic matter cycling is related to the agricultural potential of soils (Tissen et al., 1994), and that green manure production and incorporation represents an alternative source of nutrients to mineral fertilizers (Clement et al., 1998). However, it should be kept in mind that green manuring alone cannot supply sufficient essential plant nutrients for maximum or maximum economic crop yields. For example, Cherr et al. (2006b) reported that corn rotated with sunn hemp (*Crotalaria juncea* L.) plus winter green manure and supplemented with 133 kg N ha^{-1} as chemical fertilizer produced ear yields similar to monoculture corn fertilized with 200 kg N ha^{-1} as chemical fertilizer. Hence, the best strategy may be to use green manure in conjugation with chemical fertilizers. This combination may reduce application rates of inorganic fertilizers, risks of environmental pollution, and can also increase sustainability of crop production systems (Fageria, 2007).

In certain climates, green manure could have definite physicochemical advantages; in other climates, they face major constraints. For example, in temperate climates, low temperatures can hinder organic decomposition that could allow buildup of toxicity. In addition, fertilizer nitrogen is relatively easy to transport and apply, and farmers can readily adjust the timing and rate of application to meet crop requirements. Legume green manures, on the other hand, require careful management. This means that the use of green manures in crop production should be carefully evaluated for each situation.

5.3.3.1.1.2 Use of Crop Residue Crop residues can play an important role in controlling the rate of change in soil C and N content (Uhlen, 1991; Paustian et al., 1992). Kogel-Knabner (2002) and Krull et al. (2003) reported that plant litter is the primary source of SOC, while microbial residues are secondary sources. In general, as much crop residue as possible should be returned to the soil. Compared with clean tillage, minimum tillage cropping systems leave more residue on the soil surface, resulting in reduced soil erosion, less farm energy use, and greater water conservation (Unger and McCalla, 1980). Up to 70% of the total potassium accumulated in crops is found in crop residues (Fageria et al., 1990a). Complete removal of crop residues (for use as fuel, roofing, and

manufacturing) from the land causes considerable loss of nutrients and presents a great challenge to low-input farmers to develop suitable residue management techniques.

The impact of maize stover management on K balance was studied in a long-term (11 years) field experiment on a Ferrasol in Togo (Fardeau et al., 1992). These authors reported that K balance was strongly negative if straw was removed during the study. Mineral fertilizer application did not prevent depletion of soil K on this soil. By growing continuous maize, the K balance was maintained only if K fertilizer was applied and all stover was retained. This was reflected in the measured contents of available soil K at the end of the experiment: 36 and 199 mg K kg^{-1} soil, with and without removal of stover.

Optimum residue management strategies must consider the role of residues on the soil water balance, as well as their role in nutrient management. In recent years, crop residue management has been widely promoted for soil and water conservation purposes (Unger, 1994). When adequate residues are retained on the soil surface, soil water storage increased compared with residue incorporation with soil (Unger, 1984). Greater water availability to buried residues enhances their decomposition and nutrient release compared with surface residue placement (Schomberg et al., 1994). However, maximum soil protection requires that substantial residue amounts remain on the soil surface, so practices that promote rapid residue drying, such as leaving residues standing, should be encouraged on highly erodible lands. Nutrient management under these conditions may become more critical. The influence of residue quality should also be considered, that is, residues that decompose rapidly protect soils for shorter periods but accelerate the return of nutrients to the soil (Schomberg et al., 1994). In general, leafy plants decompose faster than woody plants, and leaves decay faster than roots (Wang et al., 2004). Decomposition and N release generally occur faster for residues with lower C:N, lower lignin:N ratios, and lower polyphenol concentrations (Andren et al., 1992; Vigil and Kissel, 1995; Lomander et al., 1998). Carbon:N and lignin:N ratios are usually lower for legumes compared with nonlegumes and for leaves and flowers compared with stems (Cherr et al., 2006b). Soil incorporation of plant residues may speed decomposition and N release by buffering temperature and water regimes relative to the surface (Cherr et al., 2006b). Mansoer et al. (1997) and Thonnissen et al. (2000) found more rapid decomposition and N release of soil-incorporated residues compared with residues left on the soil surface.

5.3.3.1.1.3 Use of Livestock Manures Manure from livestock is an important source of N and P for crop production in many areas, but efficient management of manure is critical to improve the economics of manure use and to minimize the impact on water quality (Jokela, 1992). Animal manures are generally required in large quantity due to their low nutrient content. Therefore, the best strategies should be to apply livestock manures in combination with inorganic fertilizers.

Soil microbial biomass is a source and sink for plant nutrients and an active participant in nutrient cycling (McGill et al., 1986). Soils managed with organic amendments generally have larger and more active microbial populations than those managed with mineral fertilizers (Bolton et al., 1985; Dick et al., 1986, 1988; Alef et al., 1988; Fauci and Dick, 1994).

5.3.3.2 Diseases, Insects, and Weeds

Diseases, insects, and weeds continue to cause major problems in agriculture throughout the world, reducing yield and quality of crops by competing for light, nutrients, and water. These biotic factors are also responsible for substantial reduction in crop yields and soil degradation. Walker (1975) suggested that overall average crop loss due to insects is 14%, to diseases 12%, and to weeds 9%. These figures are considerably less than Russell's (1978) estimate that more than half of the world's potential crop production is lost by the action of pests. The resultant losses in economic terms are impossible to estimate accurately because the severity of pests varies greatly from place to place and from year to year due to changes in environmental factors. Nematodes, weeds, and defoliating insects account for more than 85% of economic losses from biotic factors in soybean in the United States (Hammond et al., 1991).

The importance of diseases, insects, and weeds is reflected in the rapid growth of the use of pesticides in agriculture throughout the world. Weeds are the most economically important of all pests with respect to the use of pesticides and limitation to crop yield (Levesque and Rahe, 1992). An indirect measure of the impact of weeds compared with other pests in cropping systems may be the quantity of herbicide applied. Herbicides comprise 84% of the total amount of pesticides applied to wheat in the United States (Young et al., 1994). The projected herbicide use in 1992 on major field crops in the United States was 219 million kg active ingredient. Herbicides accounted for 84% of total pesticide use, while insecticides comprise 14% and fungicides 2% (USDA, 1992). Herbicide sales represent almost half of the $21 billion worldwide pesticide market (Belcher, 1989).

5.3.3.2.1 Control Measures

Best management strategies for control of diseases, insects, and weeds should employ all the technologies available rather than rely entirely on one or two measures. This is the strategy employed by the concept of integrated pest management. This means that cultural, chemical, and genetic strategies should all be applied, as appropriate, for effective pest control. An integrated disease, insect, and weed management system must take all aspects of a cropping system into account, from sowing to harvest. In addition, climate and edaphic factors, such as soil moisture and soil fertility, must be taken into account. Vegetation or crop diversity has been frequently recommended as a way of reducing pest problems, and the lack of it has been blamed for infestations (Tonhasca and Byrne, 1994). Experimental studies and theoretical arguments suggest that the differences in pest abundance between diverse and simple systems can be accounted for by the response of herbivore host-finding behavior to patterns of resource availability (Risch et al., 1983).

The impacts of pests (diseases, insects, and weeds) on crop productivity typically vary during different phases of crop development, and an effective management system should take into account the dynamic nature of crop–pest interactions throughout the growing season (Tollenaar et al., 1994a). The exploitation of beneficial effects of natural enemies by altering the soil environment is an important strategy in pest control. According to Sayre and Walter (1991), there are three types of biological control agents: (1) natural, where an agent has increased to concentrations that suppress the pest population without having been specifically introduced; (2) the augmentation of a crop or soil with an agent; and (3) the introduction of an exotic enemy with the hope that it may become established and increase to densities that have an economic impact on a pest.

Management decisions require a great deal of information regarding pest population levels and expected losses in crop value. Integrated pest management strategies are designed to employ pesticides only when pest populations reach economically damaging numbers. Furthermore, selective pesticides applied at proper times can control pests, but have minimal impact on beneficial insects (Funderburk et al., 1994).

The relative competitive ability of maize can be enhanced by increasing plant density. Tollenaar et al. (1994a) reported that increasing maize plant density from 4 to 10 plants m^{-2} reduced weed biomass up to 50%. Ghafar and Watson (1983) reported that biomass of yellow nutsedge (*Cyperus esculentus* L.) was significantly reduced when maize density was increased from 3 to 13 plants m^{-2}, and Weil (1982) reported a negative correlation between maize plant density and weed dry matter. The leaf area index of maize usually increases when plant density is increased (Tollenaar, 1992), which reduces the transmission of irradiance by the maize canopy. The leaf area index may also influence the transmitted irradiance qualitatively (i.e., the red to infrared ratio; Ballare et al., 1990), which may affect weed growth and development. Plant-suppressive rhizobacteria have the potential to be used as biological control agents to combat weeds (Johnson et al., 1993). One bacterium *Pseudomonas fluorescens* strain D_7 is a promising biological control agent, having been screened in laboratory bioassays for benign interaction with wheat roots and an inhibitory effect on downy brome roots (Kennedy et al., 1991). Application of the bacterium to winter wheat fields resulted in reduced downy brome competition and enhanced wheat yield (Kennedy et al., 1991).

Use of genetically resistant crop species and cultivars is an important pest control strategy. Recently, new possibilities have arisen to transfer desired traits (genes) not just between strains of the same species but even from one species to another, thus greatly enlarging the range of potential genetic resources available to agriculture (Hillel and Rosenzweig, 2005). Genetic yield improvement in maize has been associated with increased stress tolerance (Tollenaar, 1994b), which may suggest that modern maize hybrids are more tolerant of diseases, insects, and weed interference than earlier hybrids.

Use of genetically modified (GM) plants is an important strategy in controlling diseases, insects, and weeds. The GM plant possesses a gene or genes that have been transferred from a different species (Icoz and Stotzky, 2008). Since GM crops were first commercialized in 1996, their use has consistently increased by 10% or more each year worldwide. It is generally expected that commercial cultivation of GM crops will further increase over the coming years. The global area of GM crops increased approximately 60-fold during the 11 year period from 1996 to 2006: from 1.7 million ha to 102 million ha (James, 2006). The dominant countries planting GM crops are United States, Argentina, Brazil, Canada, India, and China. The main crops having GM genes are soybean, cotton, corn, canola, tomato, and alfalfa. However, the introduction of GM plants into agricultural ecosystems has raised a number of questions, including the ecological impact of these plants on soil ecosystems. One of the potential adverse environmental effects of GM crops is a nontarget effect on soil organisms and a change in microbe-mediated processes and functions in soil. However, Icoz and Stotzky (2008) reported that most studies have indicated few or no significant detrimental effects on microbes and other organisms in below-ground soil ecosystems.

5.3.4 Socioeconomic Factors

Among socioeconomic factors that are responsible for soil degradation, high population pressure and land tenure systems are the most important. The expanding human population, in its search for food, fiber, and fuel for today, puts tomorrow's sustainable agriculture production and natural resources preservation in jeopardy in many areas of the world (Lal, 1991). The world population in 2009 is about 6.5 billion people, and it is expected to be about 8.5 billion in the year 2025 and more than 10 billion in 2050. Most of the population increase will be in developing countries. African countries have to import food even to maintain minimum nutritional standards, and by the turn of the century, the food deficit in sub-Saharan countries will total some 50 million tons if current farming practices are not improved. The main problems in many of these areas are high population growth and low and fluctuating crop yields (International Potash Institute, 1993).

5.3.4.1 Control Measures

High population growth can be controlled by an effective family planning system. An effective family planning system involves improving the education standard of the people, improving the economic situation, and providing efficient health services at the local level. In developing countries, lack of trained medical personnel, faulty transport and communication systems, and lack of well-equipped health facilities still complicate the situation. However, with the help of international agencies and developed countries, the situation could be improved.

5.4 SUMMARY

Globally, soil degradation has accelerated as human populations have increased, threatening the stability of the earth's ecosystems, both natural and managed. Soil degradation, the loss or decline of soil productivity, is influenced by physical, chemical, and biological processes. These processes of degradation are accelerated by many of man's activities, such as deforestation, expansion of agricultural production on steep and marginal lands, monoculture, use of poor quality irrigation water,

use of excess agrochemicals, overgrazing of pasture lands, and indiscriminate use of mechanization. Soil degradation is responsible for decreasing soil fertility or the nutrient-supplying capacity of soils. By adopting appropriate soil management practices, it is possible to restore the productivity of degraded soils and, consequently, soil fertility and productivity. In addition, good soil management can ensure sufficient food for a growing world population, and will promote both human and ecosystem health. In this chapter, appropriate soil management practices are suggested to reduce soil degradation and improve nutrient use efficiency of crop plants.

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6 Remediation of Heavy Metal Contaminated Soils

6.1 INTRODUCTION

A clean environment (soil, water, and air) is a prerequisite for sustainable cropping systems, as well as human and animal health. The growth of agriculture and industry, based in large part on scientific and technological advances, has improved living standards for much of the world's population. At the same time, this growth has created environmental problems in many parts of the world. Contamination of soils with heavy metals has become a critical environmental issue because of its adverse ecological effects (An et al., 2004; Liu et al., 2007; Pinto et al., 2008). Soils contaminated with heavy metals can be found throughout the world (Cunningham et al., 1996; McGrath et al., 2002; Huang and Chen, 2003; Prista et al., 2008; Simmons et al., 2008). Industrial and mining activities have polluted soils with heavy metals in China (Wu and Zhang, 2002). Irrigation of agricultural land with sewage water containing heavy metals is a common practice in developing countries like India, because this contaminated water is also a cheap and rich source of nutrients (Singh et al., 2007). Mining and smelting operations, industrial and municipal waste, combustion of fossil fuels, and application of agricultural fertilizers can all contaminate soils with heavy metals (Chen et al., 1995; Mandal et al., 1997; Liao et al., 2005; Zhang and Duan, 2008).

The disposal of untreated industrial effluents into sewage water, and consequently, its use for irrigation has resulted in high concentration of chromium (Cr) and other heavy metals in soils and plants (Brar et al., 2000; Adhikari and Singh, 2007; Singh et al., 2007). It is estimated that in the United States alone, $6 billion per year will be required to remediate soils over the next three decades (Cunningham et al., 1996). Using various ways of defining contaminated land, it has been estimated that in the European Union alone, there are potentially 1,400,000 contaminated sites (ETCS, 1998; McGrath et al., 2002). Additionally, the presence of heavy metals in soil causes yield losses in susceptible crops (Gallego et al., 1996; Lagriffoul et al., 1998; Ali et al., 2000; Sandalio et al., 2001; McGrath and Zhao, 2003; Liu et al., 2008; Prista et al., 2008). Excess heavy metals in agricultural soils can be taken up by food crops and may pose a threat to human health as they enter the food chain (Wagner, 1993; McLaughlin et al., 1999; Hassan et al., 2008). Such a situation occurred in the 1950s and 1960s in Japan, where the cadmium (Cd) contamination of rice fields led to renal impairment and bone disease in exposed populations (Wu and Zhang, 2002). Wagner (1993) reported that renal tubular dysfunction and pulmonary emphysema are considered to be the principal pathological lesions attributable to Cd in humans, with chronic low level Cd exposure affecting bone health and causing low birth weights in certain groups of individuals. Mahimairaja et al. (2005) reported that arsenic (As) contamination in the groundwaters of West Bengal (India) and Bangladesh has caused health problems of calamitous proportions, with a significant segment of the population at high risk and with untold numbers already suffering from irreversible effects of As poisoning.

The contamination of ground and surface water by arsenic from soils and aquifers poses significant threats to human health (WHO, 2004). In the United States, arsenic is a contaminant

of concern at 508 Superfund sites, making it the second most common inorganic contaminant on the U.S. Environmental Protection Agency (USEPA) National Priority List (USEPA, 2002; Zhang and Selim, 2008). The USEPA classified arsenic as a human carcinogen and lowered the maximum contaminant level in drinking water from 50 to 10 ppb (USEPA, 2001). Groundwater As concentrations above the environmental standard have been observed in many countries including India, Bangladesh, Vietnam, China, and the United States, and have been attributed to both geologic and anthropogenic sources (Nordstrom, 2002; Smedley and Kinniburgh, 2002; Zhang and Selim, 2008). In addition, increased use of arsenic-containing compounds, such as pesticides, herbicides, wood preservatives, and livestock feed additives have introduced large amounts of arsenic into soil systems (Smith et al., 1998a,b).

Broiler production generates approximately 400 million kg of litter (a mixture of chicken manure, wasted feed, and bedding) per year in the state of Maryland in the United States, which is generally applied to fields in close proximity to the production houses (Moore, 1998; Codling et al., 2000; Sleugh et al., 2006). The broiler diet is supplemented with nutrients like phosphorus (P), copper (Cu), zinc (Zn), manganese (Mn), and arsenic (As) to stimulate growth, increase feed performance, and to ensure healthy birds (National Research Council, 1994; Driver et al., 2006). In many cases, feed supplements are added in excess of the animal's needs and are excreted in the manure (National Research Council, 1994; Moore, 1998). High soil micronutrient concentrations resulting from the repeated land application of broiler litter may negatively influence the environment through runoff and/or leaching into surface waters and ground waters (Codling et al., 2008). Among the micronutrients added to the broiler diet, As causes the greatest environmental concern because it is highly toxic (Neku and Tandukar, 2003). Peryea (1991) reported that phosphate fertilizer could induce As release from soils with high levels of As.

Arsenic contamination of surface and groundwaters occurs worldwide and has become a socio-political issue in several parts of the globe (Mahimairaja et al., 2005).

Soluble As in surface waters and groundwaters poses severe human health risks (e.g., skin legions and skin cancer). Millions of people in southeast Asia have been exposed to As levels greater than the U.S. Environmental Protection Agency (USEPA) drinking water standard ($10\,\mu g\,L^{-1}$) through the consumption of As-contaminated well water (USEPA, 2002; Meharg and Rahman, 2003). Although trace levels of As have been shown to be beneficial in plant and animal nutrition (Smith et al., 1998a,b), no comparable data are available for humans (Adriano, 2001) and elevated concentrations of As in the biosphere pose a significant threat to mankind.

Heavy metals are defined as those 38 elements whose density is higher than $5\,Mg\,m^{-3}$ (Antonovics et al., 1971; Soil Science Society of America, 1997). However, agricultural soils are mainly contaminated by Zn, Cu, Fe, Mn, Mo, Ni, Co, Pb, Cd, Hg, and Cr (Soil Science Society of America, 1997). Among these heavy metals, Zn, Fe, Mn, Cu, Mo, and Ni are essential for plant growth. Hence, their presence in the soil in adequate amounts is necessary for achieving maximum economic crop yields. Other heavy metals have no essential physiological functions in the plants. Excess amounts of both essential and nonessential heavy metals may pollute the environment and create problems for agricultural production and human and animal health (Abbaspour et al., 2008). Accumulation of heavy metals in soils may occur due to the weathering of soil parent materials, atmospheric deposition from industrial activities or power generation, the addition of industrial wastes, the disposal of municipal composts or sewage sludge, and the use of certain pesticides. For example, in the United States almost 40% of municipal wastewater biosolids are land applied to cropland (USEPA, 1995). Because of the concern over heavy metal accumulation, levels of metals that can be land applied are often regulated. The maximum concentrations of the principal heavy metals that can be applied in sewage sludge and municipal compost to croplands in Germany, Belgium, and the Netherlands, are given in Table 6.1. Similarly, the maximum concentration of metals in sewage sludge that can be applied to croplands in Virginia, USA, is given in Table 6.2. The soil application of heavy metals in

TABLE 6.1
Maximum Concentration of Principal Heavy Metals in Sewage Sludge and Compost for Application to Croplands in Belgium, the Netherlands, and Germany

Heavy Metal	Heavy Metal Limits in Sewage Sludge (mg kg^{-1} Dry Weight)	Heavy Metal Limits in Compost (mg kg^{-1} Dry Weight)[a]
Cd	39	1.1
Cr	1200	73
Pb	300	95
Hg	17	0.73
Ni	420	30
Cu	1500	63
Zn	2800	300
Mo	18	—

Sources: Adapted from Stratton, M.L. and Rechcigl, J.E., Agronomic benefits of agricultural, municipal, and industrial by-products and their co-ultilization: An overview, in *Beneficial Co-Utilization of Agricultural, Municipal and Industrial By-Products,* Brown, S. et al. (eds.), Kluwer Academic Publishers, Dordrecht, the Netherlands, 9–34, 1998; Szmidt, R., European perspective of compost co-utilization for horticulture, in *Beneficial Co-Utilization of Agricultural, Municipal and Industrial By-Products*, Brown, S. et al. (eds.), Kluwer Academic Publishers, Dordrecht, the Netherlands, 55–68, 1998.

[a] Values are averages of Belgium, the Netherlands, and Germany.

TABLE 6.2
Maximum Concentration of Heavy Metals in Sewage Sludge for Application to Croplands in the State of Virginia, USA

Heavy Metal	Concentration (mg kg^{-1})
Zinc (Zn)	2500
Lead (Pb)	1000
Chromium (Cr)	1000
Copper (Cu)	1000
Nickel (Ni)	200
Cadmium (Cd)	25
Mercury (Hg)	15

Source: Adapted from Donohue, S.J. et al., *A Handbook of Agronomy*, Virginia Cooperative Extension Service, Publication 424–100, Virginia Polytechnic Institute and State University, Blacksburg, VA, 1984.

sewage sludge is regulated, but of importance is the cumulative soil-loading levels of metals. Acceptable soil-loading levels of heavy metals are an indirect function of the soil's cation exchange capacity (CEC) (Donohue et al., 1984). Soils with higher CEC usually adsorb more metals in a plant available form. Data in Table 6.3 show that as the CEC of soils increase, more metals can be applied.

TABLE 6.3
Maximum Suggested Cumulative Application of Sludge-Born Heavy Metals to Soils Used for Food-Chain Crop Production in Virginia, USA

Heavy Metal	<5 CEC[a] (kg ha^{-1} Metal)	5–15 CEC (kg ha^{-1} Metal)	>15 CEC (kg ha^{-1} Metal)
Pb	249	498	997
Zn	124	249	498
Cd	49	100	199
Cu	2.5	5	10
Ni	498	997	1994

Source: Adapted from Donohue, S.J. et al., *A Handbook of Agronomy*, Virginia Cooperative Extension Service, Publication 424-100, Virginia Polytechnic Institute and State University, Blacksburg, VA, 1984.

[a] CEC, cation-exchange capacity of the soil.

Heavy metal accumulation in agricultural soils increases the potential for the metals to move within the environment. He et al. (2004) reported that the concentrations of Cd, Co, Cr, Cu, Fe, Ni, Pb, Zn, Mn, and Mo in the surface runoff were associated with the accumulation of the metals in soils. Heavy metals in soils and sediments are generally present in a variety of forms exhibiting different degrees of bioavailability and mobility (Salim et al., 1996). These forms are water soluble, exchangeable, carbonate associated, oxide associated, organic associated, and residual (He et al., 2004). Water soluble and exchangeable fractions readily release into the environment, whereas the residual fractions are immobile under natural conditions. The Cd, in contrast to other heavy metals, is water soluble and exhibits high mobility in soil, thus, groundwater and crops can easily become contaminated. He et al. (2004) reported that the movement of heavy metals in soils could occur in sandy, acid, and low organic matter soil if subject to heavy rainfall or irrigation.

The worldwide average content of Cd in surface soil is less than 1 mg kg^{-1}, while in plants a concentration between 5 and 30 mg kg^{-1} is toxic (Mulligan et al., 2001). Higher values reflect an anthropogenic impact, such as long-term use of phosphate fertilizers, sewage sludge application, and smelter dust deposition (Kabata-Pendias, 2001). Prista et al. (2008) reported that a Cd concentration of 20 mg kg^{-1} reduced corn growth by 20%.

Heavy metal contamination, caused by either natural processes or by human activities is one of the most serious environmental problems (Reedy and Prasad, 1990). Remediation of heavy metal contaminated soils is important to improve soil quality, sustain agroecosystems stability, and maintain a clean environment. During the past decades, the prevention of soil pollution and the cleanup of contaminated soils have become a worldwide environmental priority. The objective of this chapter is to present a detailed discussion of critical toxic levels of heavy metals in soils and plants and suggest techniques for remediation of agricultural soils contaminated with heavy metals.

6.2 ADEQUATE AND TOXIC LEVELS OF ESSENTIAL AND NONESSENTIAL HEAVY METALS IN SOIL AND PLANT TISSUES OF PRINCIPAL FOOD CROPS

Knowledge of adequate and toxic levels of essential plant heavy metals (Zn, Cu, Fe, Mn, and Mo) in the soil for food crops is important for obtaining maximum economic yields and maintaining a clean environment. If essential heavy metals are deficient, they should be added to soils with

appropriate fertilizers. If they are in the toxic range, management practices should be adopted to immobilize or phytoextract them to avoid their movement by leaching or runoff. Optimal and toxic soil levels of Zn, Cu, and Mn for principal food crops are presented in Table 6.4. Note that, the extracting solution used in heavy metal extraction from soils plays an important role in defining their adequate and toxic levels. For example, greater amounts of these heavy metals are extracted by the Mehlich-1 extracting solution than by the DTPA extractant.

TABLE 6.4
Adequate and Toxic Levels of Essential Plant Heavy Metals Extracted by Mehlich-1 and DTPA Extracting Solution in Brazilian Oxisols

	Mehlich-1		DPA	
Heavy Metal	**Adequate (mg kg^{-1})**	**Toxic (mg kg^{-1})**	**Adequate (mg kg^{-1})**	**Toxic (mg kg^{-1})**
Upland rice				
Zinc[a]	5	61	4	35
Copper[b]	2	48	1	28
Manganese[c]	8	168	4	80
Dry bean				
Zinc	0.7	25	0.3	25
Copper	1.5	35	0.5	18
Manganese	8	128	6	88
Corn				
Zinc	2	94	1	60
Copper	2.5	45	1.5	32
Manganese	8	400	4	336
Soybean				
Zinc	0.8	53	0.3	33
Copper	1	10	0.5	6
Manganese	8	92	4	56
Wheat				
Zinc	0.5	27	0.3	34
Copper	10	52	8.5	28
Manganese	8	44	3	40

Sources: Adapted from Fageria, N.K., *Rev. Bras. Eng. Agric. Ambien*., 4, 390, 2000a; Fageria, N.K., *Commun. Soil Sci. Plant Anal*., 32, 1659, 2001.

Note: The adequate level was calculated at 90% of the maximum dry weight of the shoot and the toxic level was calculated at the 10% reduction in the shoot dry weight after achieving the maximum weight.

[a] Plants were harvested at 6 weeks after sowing in the upland rice experiment, 5 weeks after sowing in the dry bean, soybean and wheat experiments and 4 weeks after sowing in the corn experiment.

[b] In the copper experiments, rice, soybean, and wheat plants were harvested 4 weeks after sowing, whereas common bean and corn plants were harvested 3 weeks after sowing.

[c] In the manganese experiment, and the rice and wheat experiments, plants were harvested at physiological maturity, whereas, common bean, corn and soybean plants were harvested 4 weeks after sowing. The soil pH at harvest was about 6.0 in water in all the five experiments.

TABLE 6.5
Adequate and Toxic Levels of Heavy Metals in the Plant Tissues of Principal Food Crops Grown on Brazilian Oxisols

Heavy Metal	Adequate Level (mg kg^{-1})	Toxic Level (mg kg^{-1})
Upland rice		
Zinc[a]	67	673
Copper[b]	15	26
Manganese[c]	520	4560
Dry bean		
Zinc	18	133
Copper	6	10
Manganese	400	1640
Corn		
Zinc	27	427
Copper	7	11
Manganese	60	2480
Soybean		
Zinc	20	187
Copper	7	10
Manganese	67	720
Wheat		
Zinc	19	100
Copper	12	17
Manganese	173	720

Sources: Adapted from Fageria, N.K., *Rev. Bras. Eng. Agric. Ambien.*, 4, 390, 2000a; Fageria, N.K., *Commun. Soil Sci. Plant Anal.*, 32, 1659, 2001.

Note: The adequate level was calculated at 90% of the maximum dry weight of the shoot and the toxic level was calculated at the 10% reduction in the shoot dry weight after achieving the maximum weight.

[a] Plants were harvested at 6 weeks after sowing in the upland rice experiment, 5 weeks after sowing in the dry bean, soybean and wheat experiments and 4 weeks after sowing in the corn experiment.

[b] In the copper experiments, the rice, the soybean, and the wheat plants were harvested 4 weeks after sowing, whereas common bean and corn plants were harvested 3 weeks after sowing.

[c] In the manganese experiment, rice and wheat experiment plants were harvested at physiological maturity, whereas common bean, corn, and soybean plants were harvested 4 weeks after sowing. The soil pH at harvest was about 6.0 in water in all the five experiments.

Adequate and toxic levels of these metals in the tissues of important food crops are presented in Table 6.5. The optimal and toxic tissue levels of these three heavy metals can be used to calibrate optimal and toxic soil test levels. Among the five crop species, upland rice and corn are more tolerant to Zn toxicity than the other three crops. Cereals are more tolerant to Cu toxicity than legume species. Upland rice and corn are more tolerant to high levels of Mn in both soils and plant tissues. Critical toxic levels of nonessential heavy metals in plants are presented in Table 6.6. The values are average values for field crops without regard to plant age or crop species.

6.3 TOLERABLE LEVELS OF HEAVY METALS IN SOIL, WATER, AND FOOD CROPS FOR HUMAN AND ANIMAL CONSUMPTION

A consumption of excessive amounts of heavy metals in food or water can be toxic to humans and animals. Table 6.7 gives what are considered safe levels of some heavy metals in soil and water. Critical levels of some heavy metals found in soils in Germany are shown in Table 6.8. Limited data are available for levels of heavy metals in foods that are considered safe for human and animal consumption. The concentrations of heavy metals in food crops are subject to regulation by national and international agencies. If adopted, the limits now being considered for Cd are 0.1 mg kg^{-1} as a guideline level and 0.2 mg kg^{-1} as the maximum level in small grains (Council of Europe, 1994). Similarly, the Chinese tolerance limit of Cd in rice grain is 0.2 mg kg^{-1} (Liu et al., 2005).

TABLE 6.6
Critical Toxic Levels of Various Nonessential Heavy Metals in Plant Tissues

Heavy Metal	Concentration (mg kg^{-1})
Cd	5–10
Hg	2–5
Co	10–20
Cr	1–2
Ni	20–30
Pb	10–20

Source: Adapted from Mengel, K. et al., *Principles of Plant Nutrition*, 5th edn., Kluwer Academic Publishers, Dordrecht, the Netherlands, 2001.

The accumulation of heavy metals in food crops is known to be affected by agronomic management practices, such as crop species and cultivar, crop rotation, fertilization, liming to adjust soil acidity, irrigation, and tillage (Grant et al., 1999; Wu et al., 2002). For example, genetic differences in the mineral uptake by crop plants were observed by Saric (1983). Table 6.9 gives Cd concentrations in straw and grain of rice cultivars. The Cd concentration in brown rice varied from 0.27 to 2.86 mg kg^{-1} with an average value of 1.40 mg kg^{-1}. Similarly, in rice straw, the Cd concentration varied from 3.97 to 32.64 mg kg^{-1}, with an average value of 14.75 mg kg^{-1}. Varieties from Japan had lower Cd concentrations in brown rice than cultivars from IRRI, China, and Southeast Asia. This means that rice genotypes differ significantly in Cd accumulation from

TABLE 6.7
International Water Quality Standard Values of Heavy Metals for Human and Livestock Consumption

Heavy Metal	Concentration for Human Consumption (mg L^{-1})	Concentration for Livestock Consumption (mg L^{-1})
Zinc	<15	<20
Molybdenum	NA	0.01
Lead	<0.10	0.05
Cadmium	<0.01	0.01
Mercury	<0.01	0.002

Sources: Adapted from Lal, R., Water quality effects of tropical deforestation and farming system on agricultural watersheds in Western Nigeria, in *Soil Processes and Water Quality*, Lal, R. and Steward, B.A. (eds.), Lewis, Boca Raton, FL, 273–301, 1994; Sahrawat, K.L. et al., Measurable biophysical indicators for impacting assessment: Changes in water availability and quality, in *Natural Resources Management in Agriculture: Methods for Assessing Economic and Environmental Impacts*, Shiferaw, B. et al. (eds.), CAB International, Wallingford, U.K., 75–96, 2005.

Note: NA, not available.

Cd-contaminated soils, and a selection of cultivars that accumulate less Cd can greatly reduce human consumption of this toxic metal. Plant breeders have achieved reductions in the uptake and translocation of Cd to edible tissues of sunflower (Li et al., 1995).

6.4 HEAVY METALS REMEDIATION TECHNIQUES

Soil is the principal source of heavy metal accumulation by plants. Many characteristics, such as the concentration and the form of metal in the soil, the pH, the organic matter content, the clay content, the concentration of other cations, complexing ligands, and fertilizer practices have been recognized as major factors that determine the bioavailability of heavy metals in soils (Smolders et al., 1998; Norvell et al., 2000). A variety of thermal, chemical, and physical methods can be used to remove heavy metal contaminants from soils (Nyer, 1992). These techniques can be divided into two groups. The first uses soil amendments, like lime and organic matter, and adequate fertilizer rates. The second group uses plants to remove heavy metals from the soil. This technique is known as phytoremediation or phytoextraction. The goal of phytoextraction is to use plants to absorb heavy metals from the soil and sequester them in their shoots, which can then be harvested and safely disposed of (Kumar et al., 1995; Hamlin and Barker, 2008). A phytoremediation-efficient species produces high shoot biomass and accumulates large amounts of the pollutant or its metabolites in the aboveground part, without any adverse effects on plant growth (Cunningham and Ow, 1996; Blaylock et al., 1997; Meagher, 2000; Vassilev et al., 2002). Soil microorganisms may also be used to stabilize heavy metals, making them less toxic or mobile. All remediation techniques either remove the contaminant from the polluted soil matrix in a process called decontamination or sequester the contaminant via stabilization (Cunningham et al., 1996; Meagher, 2000).

TABLE 6.8
Critical Toxic Levels of Nonessential Heavy Metals for Agricultural Soils of Germany

Heavy Metal	Content (mg kg^{-1})
Ni	50
Cd	3
Pb	100
Cr	100
Hg	2

Source: Adapted from Mengel, K. et al., *Principles of Plant Nutrition*, 5th edn., Kluwer Academic Publishers, Dordrecht, the Netherlands, 2001.

TABLE 6.9
Cadmium Concentration in Brown Rice and Straw of Rice Cultivars of the International Rice Research Institute (IRRI), China, Japan, and Southeast Asia Grown in Soil Containing 100 mg kg^{-1} Cadmium

Cultivar/Origin	Cd Conc. (mg kg^{-1}) in Brown Rice	Cd Conc. (mg kg^{-1}) in Straw
IR24 (IRRI)	2.36	32.64
IR841 (IRRI)	2.37	13.90
IR36 (IRRI)	2.72	30.09
Ming hui 63 (China)	2.86	25.45
Yang dao 2 (China)	1.33	6.47
Nan jing 16 (China)	1.13	5.06
Yu 44 (Japan)	0.27	11.94
Guan dong 125 (Japan)	0.37	5.59
Nong ken 57 (Japan)	0.52	3.97
CV6 (Southeast Asia)	1.20	15.73
NPT3 (Southeast Asia)	1.36	11.38
Average	1.40	14.75

Source: Adapted from Liu, J. et al., *J. Sci. Food Agric.,* 85, 147, 2005.

6.4.1 Liming

Liming is the practice of adding liming materials to acid soils to increase the soil supply of Ca and Mg, or raise soil pH and reduce the toxicity of heavy metals. Soil pH is a critical factor influencing many chemical reactions in the soil environment (Anderson and Christensen, 1988; Basta and Tabatabai, 1992; Fageria et al., 1997; Norvell et al., 2000; Mengel et al., 2001; Brady and Weil, 2002; Khoshgoftar et al., 2004). In addition, liming increases the cation exchange capacity (CEC) of soils and reduces soil solution concentrations of cations other than the added Ca and Mg (Helyar and Anderson, 1974).

In general, heavy metal uptake by plants decreases as soil pH increases, and application of lime has been suggested as a measure to reduce heavy metal bioavailability by crop plants (Pierzynski and Schwab, 1993; Ohtani et al., 2007). In soil–plant systems, the bioavailability of heavy metals is primarily controlled by adsorption–desorption reactions at the particle–solution interface (Backes et al., 1995; Glover et al., 2002). Most heavy metals are adsorbed or precipitated when pH is raised from acidic to neutral. The data presented in Table 6.10 show that water-extractable Cu and Fe of a Brazilian Inceptsol decreased significantly when soil pH was raised from 4.9 to 7.0. Similarly, the uptake of Fe, Mn, Cu, and Zn by upland rice was significantly decreased when pH of a Brazilian Oxisol was raised from 4.6 to 6.8 (Table 6.11).

TABLE 6.10
Influence of Soil pH on Copper and Iron Content of a Brazilian Inceptisol

Soil pH in H_2O	Cu (mg kg^{-1})	Fe (mg kg^{-1})
4.9	6.3	297
5.9	6.3	231
6.4	5.8	187
6.7	5.0	158
7.0	3.3	148
R^2	0.94**	0.55**

Source: Adapted from Fageria, N.K. and Baligar, V.C., *J. Plant Nutr.,* 22, 1495, 1999.

** Significant at the 1% probability level.

TABLE 6.11
Influence of Soil pH on Uptake of Iron, Manganese, and Zinc by Upland Rice Grown on Brazilian Oxisol

Soil pH in H_2O	Fe (μg $Plant^{-1}$)	Mn (μg $Plant^{-1}$)	Zn (μg $Plant^{-1}$)
4.6	4,541	11,165	1,090
5.7	1,856	5,006	300
6.2	1,978	4,309	242
6.4	1,634	3,607	262
6.6	1,663	2,762	163
6.8	1,569	2,359	142
R^2	0.97**	0.99**	0.98**

Source: Adapted from Fageria, N.K., *Pesq. Agropec. Bras*., 35, 2303, 2000b.

** Significant at the 1% probability level.

Zinc and Cd adsorption by soil increased significantly when soil pH was raised above 5 and reached a maximum at pH values between 6 and 7, when adsorption was almost 100% (Saha et al., 2001). Soil solution Cd concentration decreased as pH increased from 3 to 8 (Andersen et al., 2002). Several authors also reported that Cd release from soil increases substantially when pH drops below 4.5 (Bergkvist et al., 1989; McBridge et al., 1997). Glover et al. (2002) reported a linear decrease in soil sorption of Pb and Cd when soil pH was increased from 3 to 9. Similarly, Harter and Naidu (2001) reported that Zn sorption by soil increased almost linearly with an increase in pH from 4.5 to 7.5. Naidu et al. (1994) reported that Cd sorption was significant when soil pH was raised from 2.5 to 6. Boekhold et al. (1993) reported a doubling of Cd sorption for each 0.5 increase in pH between 3.8 and 4.9. The increase in sorption of heavy metals with increasing pH is usually assumed to be the result of both change in the surface charge of soils and shifts in soil solution ionic species (Harter and Naidu, 2001).

A reduction in Ni uptake by plants due to increasing soil pH of acid soils has been reported (Halstead et al., 1969; Mishra and Kar, 1971). Treating agricultural soils with alkaline stabilized biosolid helps to overcome the phytotoxicity of Ni (Boltan, 1975). Alkaline stabilized biosolids are now becoming increasingly popular as a liming material because of the complementary effects of organic matter in immobilizing metals in soils (Bolan et al., 2003).

The behavior of Mo is different compared to other heavy metals in relation to change in soil pH. Goldberg et al. (2002) determined molybdenum adsorption by soils to be a function of pH. They concluded that Mo adsorption by soils was maximal in the pH range 2–5 and decreased rapidly as pH increased from 5 to 8, and was minimal above pH 9. Low pH also lowered the CEC of soil organic matter and mineral surfaces, thereby weakening the adsorption of metals to specific sites (Bolan et al., 2003).

6.4.2 Improving Soil Organic Matter Content

Soil organic matter plays a vital role in improving soil quality. It is a storehouse for nutrient accumulation, water storage, and beneficial microbial activities. It also helps reduce soil erosion and maintains the sustainability of agroecosystems. Soil organic matter can be improved by the addition of farmyard manures, the incorporation of crop residues, the use of green manuring, by reducing tillage, and keeping farmland fallow or under pastures. The humic materials contained within soil organic matter are important environmental sinks for toxic metals because they contain organic ligands that form stable complexes with metals, preventing their release to soil solution and leaching into ground water (Bolton et al., 1996). The complexing capacity of these organic ligands is controlled by the composition and the structure of the humic materials present in soil (Sposito, 1986).

Organic matter increases the cation exchange capacity of soils, which increases soil adsorption of heavy metals. Organic ligands increase heavy metal sorption to soil surfaces by increasing the negative electrostatic potential on the surfaces, which increases adsorption of the metals (Naidu and Harter, 1998). The presence of organic ligands may also inhibit the crystallization of some Fe hydroxides. As the negative surface charge of these hydroxides increases, the capacity for metal adsorption may also increase (Xue and Huang, 1995). Organic matter is extremely effective at alleviating the toxicity of metals in slagheaps, permitting a healthy growth of various non-tolerant species for several years (Hilton, 1967).

In a study with 24 British soils, McLaren and Crawford (1973) concluded that the majority of the available Cu exists in an organically bound form. Udo et al. (1970) noted a strong correlation between total soil Zn and organic matter content, and concluded it was an important soil component responsible for Zn retention in calcareous soils. Elliott et al. (1986) reported that for Cd and Cu, increased soil organic matter should restrict mobility and bioavailability, at least under acidic conditions where soluble metal complex formation is limited. Copper has low leachability because it complexes with organic matter (Fageria, 2009). Zinc generally does not move through the soil profile because of its affinity to bind to organic matter (Codling et al., 2008).

6.4.3 Use of Adequate Rates of Fertilizers

The application of adequate rates of fertilizers can reduce the phytotoxicity of heavy metals. Antosiewicz (1995) reported that the use of adequate amounts of P and Mg can alleviate the toxic effects caused by metal exposure. Use of adequate rates of N, K, Ca, Mg, and Mo to soils reduces the toxic effects of Ni in crop plants (Mishra and Kar, 1971). Hunter and Vergnano (1952) reported that the application of N and K fertilizers could correct nickel toxicity in crop plants. Mishra and Kar (1971) reported that the application of Mo to the soil and the foliage decreased the severity of chlorosis and other toxic effects of Ni. These authors reported that this corrective treatment for Ni toxicity was due to the antagonistic effect of Mo on Ni. In contrast, P fertilization tends to enhance the toxic effects of Ni (Halstead et al., 1969; Mishra and Kar, 1971).

Wu and Zhang (2002) reported that Zn application reduced Cd uptake by barley plants. The addition of Zn to soil has been shown to reduce crop Cd concentration (Cataldo et al., 1983; Choudhary et al., 1995). Oliver et al. (1994) reported that Cd concentration of wheat grain was reduced with the application of Zn in areas of marginal to severe Zn deficiency.

6.4.4 Phytoremediation

The generic term "phytoremediation" consists of the Greek prefix *phyto* (plant) attached to the Latin root *remedium* (to correct or remove evil) (Cunningham et al., 1996). Phytoremediation is the use of plants to extract heavy metals from contaminated water and soils (Lopez et al., 2007). Salt et al. (1998) defined phytoremediation as the use of green plants to remove pollutants from the environment or to render them harmless. McGrath et al. (2002) defined it as the use of plants to improve the environment. Phytoremediation is also known as phytoextraction, and it is sometimes the most economical and environmentally clean technology for remediation of sites contaminated with toxic elements.

A great deal of research indicates that plants have the potential to remove many toxic metals from the soil (Antonovics et al., 1971; Baker et al., 1991; Lasat, 2002; Malarkodi et al., 2008). The potential of plants to remove metals in their shoots is determined by their ability to produce abundant shoot mass rapidly and with high concentrations of the targeted metals (Cunningham and Ow, 1996; Blaylock et al., 1997; Hamlin and Barker, 2006). McGrath et al. (2002) reported that the efficiency of phytoextraction is ultimately the product of a simple equation: biomass × element concentration in biomass. Brooks et al. (1977) first introduced the term "hyperaccumulators" to describe plants capable of accumulating more than 1000 μg Ni g^{-1} on a dry-leaf basis in their natural habitats. The criterion for defining Co, Cu, Pb, and Se hyperaccumulation is also 1,000 μg g^{-1} in the shoot dry matter, whereas for Zn and Mn the threshold is 10,000 μg g^{-1} and for Cd 100 μg g^{-1} (Brooks, 1998; Baker et al., 2000). Although these criteria are quite arbitrary, in general the concentrations of metals in hyperaccumulator plants are about 100–1000-fold higher than those in normal plants growing on soils with background metal concentrations, and about 10–100-fold higher than most other plants growing on metal-contaminated soils (McGrath et al., 2002).

Several accessions of Indian mustard (*Brassica juncea* Czern.) exhibit favorable traits for phytoextraction, including the ability to accumulate metals such as Cd, Cu, Cr, Ni, Pb, and Zn (Dushenkov et al., 1995; Salt et al., 1995; Blaylock et al., 1997; Ebbs and Kochian, 1998). Similarly, wild castor (*Ricinus communis* L.) and marigold (*Tagetes erecta* M.) plants have been reported to be good metal accumulators (Malarkoid et al., 2008).

For phytoremediation of contaminated soils, plants capable of accumulating high levels of metals are grown, and when they mature metal-enriched aboveground biomass is harvested and removed (Lasat, 2002). The use of plants for bioremediation is not new; the first plant-based system was installed over 300 years ago in Germany for the treatment of municipal sewage (Cunningham et al., 1996).

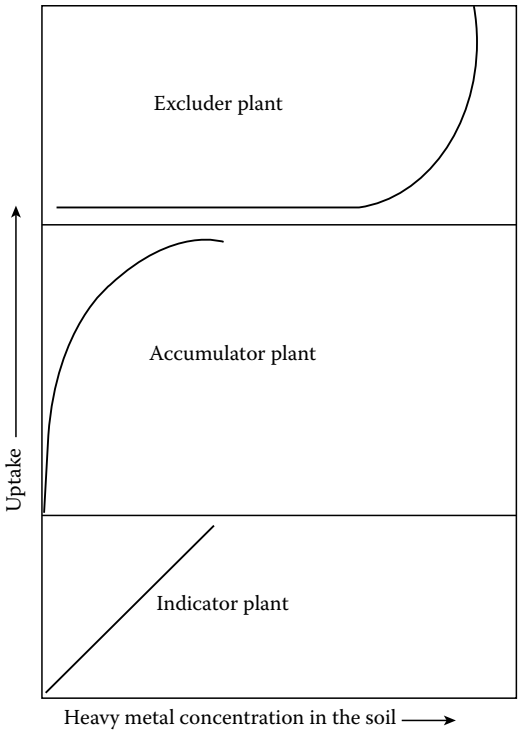

FIGURE 6.1 Hypothetical uptake pattern of heavy metals by indicator, accumulator, and excluder plant species.

Plant species capable of growing on metal-contaminated soils are tolerant of high concentrations of metals in the soil. Three kinds of physiological mechanisms for high soil metal concentration have been identified (Baker, 1981). These groups are (1) indicator plants, (2) accumulator plants, and (3) excluder plants. In indicator plants, the metal uptake is linearly related to the metal concentration in the soil. In the case of metal accumulator plants, the accumulation of heavy metals is high at lower as well as at higher metal concentrations in the soil. In contrast, excluder plants take up very little metal below a critical level of soil metal concentration, then their uptake increases greatly with increasing soil concentrations. The metal uptake characteristics of these three plant types are shown in Figure 6.1.

Some plants can effectively avoid root uptake of metals by producing root exudates that form complexes with the metals outside the root (external defense mechanisms). After uptake by the roots, the toxicity of metal ions may be reduced by formation of metal complexes inside the plant cells (internal defense mechanisms) (Pinto et al., 2006). In tolerant plants, trace metals are very often chelated or precipitated inside the vacuoles, indicating transport through the cytosol (Leopold et al., 1999). Glutathione and related phytochelatins are the main metal-sequestrating molecules in the cytosol (Leopold et al., 1999, Cobbert, 2000; Pinto et al., 2006).

A number of heavy metal indicator species, accumulator species, and excluder species are given in Tables 6.12, 6.13, and 6.14, respectively. Detailed discussions of the phytoremediation of inorganic compounds have been presented by Baker et al. (1991), Kumar et al. (1995), and Salt et al. (1998).

6.4.5 Phytodegradation

Plants and associated microorganisms can be used to degrade organic pollutants through a process known as phytodegradation (Salt et al., 1998). Soil microorganisms possess several mechanisms capable of altering metal bioavailability (Lasat, 2002). Soil microbes have been reported to be decrease the bioavailability of metals via precipitation (Kelley and Tuovinen, 1988). A strain of

TABLE 6.12
Heavy Metal Indicator Plants under Different Agroecological Regions

Plant Species	Family	Metal	State/Country
Alyssum bertolonii	Cruciferae	Ni	Zimbabwe
Alyssum murale	Cruciferae	Ni	Zimbabwe
Albizia amara	Leguminosae	Ni	Zimbabwe
Dioma macrocephala	Compositae	Ni	Zimbabwe
Barleria aromatica	Acanthaceae	Ni	Zimbabwe
Combretum molle	Combretaceae	Ni	Zimbabwe
Dalbergia melanoxylon	Leguminosae	Ni	Zimbabwe
Eminia atennulifera	Leguminosae	Ni	Zimbabwe
Turraea nilotica	Meliaceae	Ni	Zimbabwe
Alyssum murale	Cruciferae	Ni	Georgia, Soviet Union
Tephrosia spp.	Leguminosae	Pb, Zn	Australia
Polycarpaea synandra	Caryophyllaceae	Pb, Zn	Australia
Tephrosia affinpolyzyga	Leguminosae	Pb, Zn	Australia
Gomphrena canescens	Amaranthaceae	Pb, Zn	Australia
Amorpha canescens	Papilionaceae	Pb	Michigan/Wisconsin, USA
Rhus spp.	Anacardiaceae	Pb	Missouri, USA
Sassafras spp.	Lauraceae	Pb	Missouri, USA
Viola calaminaria	Violaceae	Zn	Belgium, Germany
Philadelphus spp.	Philadelphaceae	Zn	Washington, USA
Ruta latifolia	Rutaceae	Zn	Brazil
Senecio brasiliensis	Compositae	Zn	Brazil
Ruta graveoleus	Rutaceae	Zn	Brazil, USA
Matricaria americana	Compositae	Zn	Brazil
Ambrosia spp.	Compositae	Zn	The United States
Populus deltoides	Salicaceae	Zn	The United States
Arabis halleri	Cruciferae	Zn	Germany
Thlaspi cepeaefolium	Cruciferae	Zn	Austria, Italy
Polycarpaea glabra	Caryophyllaceae	Cu	Australia
Gypsophila patrini	Caryophyllaceae	Cu	Soviet Union
Elshotzia haichowen	Labiatae	Cu	China
Merceya latifolia	Moss	Cu	Sweden
Ocinum homblei	Labiatae	Cu	Zimbabwe
Silene otites	Carophyllaceae	Cu	Germany
Olax obtusifolia	Olacaceae	Cu	Zimbabwe
Eschscholtzia mexicana	Papaveraceae	Cu	Arizona, USA
Viscaria alpina	Carophyllaceae	Cu	Norway
Astragalus declinatus	Leguminosae	Cu, Mo	Armenia, Soviet Union
Alsine setaceae	Caryophyllaceae	Hg	Spain

Source: Adapted from Antonovics, J. et al., *Adv. Ecol. Res*., 7, 1, 1971.

Xanthomonas maltophyla catalyzes the reduction and the precipitation of highly mobile Cr^{6+} to Cr^{3+}, a significant less mobile and environmentally less hazardous compound (Blake et al., 1993; Lasat, 2002). The same strain also made the transformation of other metals like Pb^{2+} and Hg^{2+} to less available forms (Lasat, 2002). Microbial strains of *Escherichia coli* and *Pseudomonas putida* also had similar characteristics (Wang and Shen, 1995, 1997).

Plants function as the principal entry points of heavy metals into the foods of humans and animals (Rauser, 1990). Ecto- and endomycorrhizal symbiosis can play crucial roles in protecting

TABLE 6.13
Heavy Metal Accumulator Plant Species

Heavy Metal	Plant Species	Conc. in Shoot (mg kg^{-1})
Mn	*Macadamia neurophylla*	51,800
Zn	*Thlaspi caerulenscens*	51,600
Ni	*Psychotria douarrei*	47,500
Cu	*Ipomoea alpina*	12,300
Co	*Haumaniastrum robertii*	10,200
Pb	*Thlaspi rotundifolium*	8,200
Cd	*Thlaspi caerulescens*	1,800

Sources: Adapted from Baker, A.J.M. and Walker, P.L., Ecophysiology of metal uptake by tolerant plants, in *Heavy Metal Tolerance in Plants: Evolutionary Aspects*, Shaw. A.J. (ed.), CRC Press, Boca Raton, FL, 155–177, 1990; Jaffre, T. et al., *Science*, 193, 579, 1976; Brown, S.L. et al., *J. Environ. Qual*., 23, 1151, 1994; Cunningham, S.D. and Ow, D.W., *Plant Physiol*., 110, 715, 1996.

TABLE 6.14
Heavy Metal Excluder Plant Species

Plant Species	Heavy Metal Excuder
Silene vulgaris	Zn, Cu
Armeria maritima	Zn, Pb, Cu
Thlaspi alpestre	Pb
Minuartia verna	Pb
Trachypogon spicatus	Cu
Stereochlaena cameronii	Cu

Source: Adapted from Baker, A.J.M., *J. Plant Nutr*., 3, 643, 1981.

plant roots from heavy metal toxicity (Galli et al., 1994). The efficiency of protection, however, differs among isolates of mycorrhizal fungi and among heavy metals. Fungal ecotypes from heavy metal contaminated sites seem to be more tolerant to heavy metals than reference strains from non-contaminated sites (Gildon and Tinker, 1983; Galli et al., 1994). The heavy metals taken up into the cells of the fungal mycelium seem to be bound by N and S, indicating heavy metal-thiolate binding in metallothionein-like peptides (Galli et al., 1994).

6.5 SUMMARY

Public concerns over heavy metal contamination in both soils and waters have substantially increased in recent years. Unlike organic compounds, metals are not degraded in soils. Heavy metal contaminated soils pose potential threats to food quality, human and animal health, and the environment. Their remediation is an important aspect for soil quality and the production of healthy foods. The bioavailability of heavy metals to plants is associated with many soil properties,

including pH, organic matter content, concentration and form of metal in the soil, and the concentration of other cations and complexing ligands.

Heavy metals are 38 in number, the elements whose density is higher than 5.0 Mg m^{-3}. Those of greatest concern in soils include zinc (Zn), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni), cobalt (Co), lead (Pb), cadmium (Cd), mercury (Hg), and chromium (Cr). Among these heavy metals, Zn, Cu, Fe, Mn, Mo, and Ni are essential for the growth and development of plants. Hence, the presence or the addition of these essential elements to soil in adequate amounts is necessary for achieving maximum economic yields of crops. Sometimes, these essential elements accumulate in higher amounts than what is necessary for growth, and at high concentrations they, like the nonessential heavy metals, can be toxic to plants. Heavy metals can accumulate in soils by the weathering of soil parent materials, as well as disposal of industrial wastes, municipal composts, and sewage sludge on soils, through the application of certain pesticides containing heavy metals. The major techniques used for remediation of heavy metal contaminated soils are the application of soil amendments (like agricultural lime and organic materials) and phytoremediation. The use of amendments immobilizes the heavy metals in the soil, minimizing their loss in the runoff and their leaching into ground waters. Phytoremediation involves the use of plants for phytostabilization and phytoextraction of metals from the soil solution. Plant species used for remediation of metal-contaminated soils have been divided into three groups. These plants are known as indicator plants, accumulator plants, and excluder plants. Heavy metal accumulation in plants is genetically controlled, and sometimes plants useful for remediation of metal-contaminated soils are adapted to specific agroecological conditions. The main heavy metal defense mechanisms developed by plants are the synthesis of phytochelatins that can detoxify metals inside the cytoplasm of plant cells and serve as metal carriers to the vacuoles. Both the application of soil amendments and phytoremediation can be cost effective and environmentally sound methods of treating soils contaminated with heavy metals. In addition, both techniques can be used together for economical and ecologically sound results.

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7 The Effects of Essential Nutrients on Plant Diseases

7.1 INTRODUCTION

Essential plant nutrients in adequate amounts are necessary to improve crop yields, plant health, and quality. Their judicious use is fundamental to improve production efficiency, reduce production costs, and maintain sustainability of cropping systems. Crop responses to mineral nutrients may be conducive or adverse to diseases, depending on disease type, severity, crop species, and cultivar. Graham (1983) reported that since higher plants and their pathogens have coexisted over evolutionary periods of time, most relationships have achieved a balance, neither the host nor the pathogen having eliminated the other. In most situations, balanced mineral nutrition improves the plant's ability to resist diseases, and adequate rate, form, and balance of mineral nutrition are fundamental for disease management (Fageria, 2009). Research on the influence of mineral nutrition on plant diseases is very limited, and most of the work has not involved specialists in plant pathology, mineral nutrition, and agronomy. For example, to study the influence of a particular nutrient on diseases, the nutrient in question should be applied at a wide range of rates, while other nutrients should be applied in adequate amounts. In addition, most of the research on this topic has been conducted under greenhouse conditions, which may not be applicable to field conditions.

Certain tillage practices and climatic conditions, monoculture cropping systems, and year-round cultivation can be conducive to pathogen buildup, leading to significant disease pressures on crop growth, yield, and/or quality. Protection measures vary widely in availability, effectiveness, and economic feasibility. In some cases, pesticides are available and can be economically utilized. Crop rotations are possible in some cases. Genetic resistance to specific disease organisms exists for some crops. Balanced nutrition may be another factor that increases resistance to disease (Usherwood, 1980; Fageria, 2009).

Plant diseases are greatly influenced by environmental factors, including deficiencies and/or toxicities of essential nutrients. The effects of nutrients on disease may be attributed to (1) effects on plant growth that can influence the microclimate in a crop and thereby affect infection by the pathogen, (2) effects on cell walls and tissues, as well as on the biochemical composition of the host, (3) the rate of growth of the host, which may enable seedlings to escape infection in their most susceptible stage, and (4) effects on the pathogen through alterations in the soil environment (Colhoun, 1973).

Balanced nutrition has an important role in determining plant resistance or susceptibility to diseases. A severely nutrient-stressed plant is often more susceptible to disease than one at a nutritional optimum; yet plants receiving a large excess of a required mineral may become predisposed to disease (Piening, 1989). Mineral elements are directly involved in all mechanisms of plant defense as integral components of cells, substrates, enzymes, and electron carriers, or as activators, inhibitors, and regulators of metabolism (Huber, 1980).

Crop losses can be the result of reduced quantity and/or quality of yield. Losses resulting from diseases, insects, and weeds constitute one of the most significant constraints worldwide to increasing food production. Losses are the result of changes in the structure or condition of a crop to an extent that restoration of yield and/or quality is not possible (Zadoks and Schein, 1979). Preharvest losses caused by diseases, insects, and weeds have been estimated at 35%, whereas postharvest losses and wastage are reported at 30% (James, 1980). This means that, potentially, most world food problems could be eliminated just by reducing the losses caused by diseases, insects, and weeds.

By effecting changes in growth patterns, plant morphology and anatomy, and, particularly, chemical composition, mineral nutrients may either increase or decrease the resistance of plants to pathogens (Marschner, 1995). Because of the importance of the subject, an overview of the relations between essential nutrients and plant diseases is presented in this chapter. Other reviews include those of Huber and Watson (1974), Perrenoud (1977), Huber (1980), Graham (1983), Huber and Arny (1985), Marschner (1995), Huber and Wilhelm (1988), Huber and Thompson (2007), Prabhu et al. (2007a,b), Graham and Stangoulis (2007), Rahman and Punja (2007), and Jones and Huber (2007). Information provided herein will help in planning better strategies of disease control and, consequently, will improve crop production.

7.2 NITROGEN

Nitrogen has profound effect on growth and development of crop plants under most agroecosystems, hence on plant diseases (Huber and Watson, 1974; Huber and Thompson, 2007). Nitrogen uptake is usually the fourth most abundant element in crop plants, exceeded only by carbon, hydrogen, and oxygen, though for a few crops, like rice, uptake of K may exceed that of N (Fageria, 2009). Mineralization of N in the soils takes place through microbial activities, and its uptake by plants is in the form of either NH_4^+ or NO_3^-. Most plants can use either form of inorganic N, although some plants may be better adapted to one or the other form (Huber and Thompson, 2007; Fageria, 2009). In oxidized soils, NO_3^- is usually the dominant form of N take-up by plants. Stabilizing N as NH_4^+ by inhibiting nitrification can improve the efficiency of N uptake and reduce the severity of several diseases through the form of N effect (Huber, 1991; Huber and Thompson, 2007).

The evidence that excessive nitrogen fertilization increases susceptibility of host plants to obligate pathogens (e.g., rust, powdery mildew, clubroot) seems to be conclusive, although the form of nitrogen available to the plant may also be significant (Huber and Watson, 1974; Kiraly, 1976; Huber and Thompson, 2007). However, high levels of nitrogen usually increase resistance to facultative pathogens in fresh, green, young plant tissues (Kiraly, 1976). Table 7.1 shows the effects of low and high nitrogen on diseases caused by obligate and facultative pathogens. These differences in response result from differences in the nutritional requirements of the two types of pathogens. Obligate pathogens rely on assimilates supplied by living cells. Facultative pathogens, on the other hand, are semisaprophytes that prefer senescing tissue or that release toxins in order to damage or kill the host plant cells. As a rule, all factors that support the metabolic and synthetic activities of host cells and delay senescence of the host plant also increase resistance to facultative pathogens

TABLE 7.1
Effects of Low and High Nitrogen Concentrations on Disease Severity[a]

Pathogen or Disease		Low N	High N
Obligate parasites	*Puccinia graminis*	*	***
	Erysiphe graminis	*	***
	Plasmodiophora brassicae	*	*
	Tobacco mosaic virus	*	***
Facultative parasites	*Xanthomonas vesicatoria*	***	*
	Alternaria solani	***	*
	Fusarium oxyporum	***	*

Source: Adapted from Kiraly, Z., Plant disease resistance as influenced by biochemical effects on nutrients in fertilizers, in *Fertilizer Use and Plant Health*, International Potash Institute, Bern, Switzerland, 1976.

[a] Disease severity: ***, high; *, low.

TABLE 7.2
Influence of Nitrogen on Plant Diseases of Principal Field Crops

Crop Species	Disease	Pathogen or Causal Agent	Disease Increase (I) or Decrease (D)[a]
Peanut	Pod rot	*Pythium, Rhizoctonia, fusarium* spp.	I
Peanut	Black rot	*Cylindrocladium crotalaria*	D
Upland rice	Blast	*Pyricularia oryzae*	I
Snap bean, lima bean	Damping-off	*Rhizoctonia*	I
Potato	Early blight	*Alternaria solani*	D
Wheat	Eyespot	*Pseudocercosporella herpotrichoides*	I (NH_4^+) or D (NO_3^-)
Wheat	Take-all	*Gaeumannomyces graminis*	D (NH_4^+) or I (NO_3^-)
Corn	Gray leaf spot	*Cercospora zeaemaydis*	I
Cotton	Leaf spot	*Alternaria macrospora*	D (NH_4^+)
Cotton	Root rot	*Phymatotrichum omnivorum*	D
Wheat	Mildew	*Erysiphe graminis*	I
Soybean	Stem canker	*Diporthe phaseolorum*	D
Soybean	Mosaic	*Mosaic virus*	I
Rape, canola	Root rot	*Rhizoctonia solani*	D
Pea	Root rot	*Fusarium* spp.	I (NH_4^+) or D (NO_3^-)
Sunflower	Stem rot	*Sclerotinia sclerotiorum*	D

Source: Compiled from Huber, D.M. and Thompson, A., Nitrogen and plant disease, in *Mineral Nutrition and Plant Disease,* Datnoff, L.E. et al. (eds.), The American Phytopathological Society, St. Paul, MN, 31–44, 2007.

[a] In most of the cases, N source was not specified.

(Marschner, 1995). The effect of N on crop diseases of principal field crops is summarized in Table 7.2, which shows that increasing N uptake can increase or decrease diseases in crops, depending on crop species and also in some cases on N source.

The form of nitrogen (N) has an important role in plant disease. A critical NH_4^+–N:NO_3^-–N ratio for take-all suppression of 3:1 was estimated from data in the literature (Christensen and Brett, 1985). Take-all severity was negatively correlated ($r^2 = 0.84$) with the length of time the NH_4^+–N:NO_3^-–N ratio remained above the estimated critical ratio.

Urea applied to the foliage of wheat has reduced levels of *Septoria tritici*, *S. nodorum*, powdery mildew (*Erysiphe graminis*), and brown rust (*Puccinia recondita*) in some experiments (Gooding et al., 1988; Peltonen et al., 1991). It has been suggested that increased leaf nitrogen content can improve resistance to *Septoria* spp. infection (Zadoks and Schein, 1979), and this is consistent with the finding that increasing soil applications of granular ammonium nitrate in the spring can also sometimes lead to lower levels of late-season *S. tritici* (Gooding and Davies, 1992). Additionally, experiments on agar have found spore germination and colony growth of *S. nodorum* to be inhibited by urea addition (6%), and scanning electron micrographs suggest that urea inhibits spore germination on the surface of wheat leaves (Peltonen et al., 1991). Furthermore, foliar urea applications influence microflora populations on the surface of cereal leaves, and these can interact with cereal pathogens.

Sometimes foliar urea applications have increased the severity of *Botrytis cinerea* (Gooding et al., 1988) and *S. nodorum* infection. It is suggested that damage by urea sprays to leaf tissue is likely to encourage secondary invasion of the scorched areas by certain pathogens, where the subsequent microclimate encourages these infections. Increased severity of *S. nodorum* appears to be more likely when applications of urea are made subsequent to infection (Gooding and Davies, 1992). Increased fertilizer N rates caused increased eyespot and crown rot of wheat, but the effects

TABLE 7.3
Influence of Soil pH and Nitrogen Form on Plant Diseases

		pH		Nitrogen Form	
Plant	**Disease**	**Low**	**High**	**Ammonia**	**Nitrate**
Cereals	Take-all	Decrease	Increase	Decrease	Increase
Cotton	*Phymatotrichum* root rot	Decrease	Increase	Decrease	Increase
Cotton	*Verticillium* wilt	Decrease	Increase	Decrease	Increase
Eggplant	*Verticillium* wilt	Decrease	Increase	Decrease	Increase
Potato	*Verticillium* wilt	Decrease	Increase	Decrease	Increase
Potato	*Streptomyces* scab	Decrease	Increase	Decrease	Increase
Tobacco	*Thielaviopsis basicola*	Decrease	Increase	Decrease	Increase
Tomato	*Verticillium* wilt	Decrease	Increase	Decrease	Increase
Turf	Take-all	Decrease	Increase	Decrease	Increase
Wheat	*Fusarium* root rot	Decrease	Increase	—	Increase
Avocado	Black rot	Increase	Decrease	—	Increase
Bean	*Fusarium* root rot	—	—	Increase	Increase
Brassicae	Clubroot	Increase	Decrease	—	—
Cotton	*Fusarium* wilt	Increase	Decrease	Increase	Decrease
Many	*Sclerotium* collar rot	Increase	Decrease	Increase	Decrease
Pea	*Aphanomyces euteiches*	Increase	Decrease	—	—
Peach	Bacterial canker	Increase	Decrease	—	—

Source: Compiled by Huber, D.M. and Wilhelm, N.S., The role of manganese in resistance to plant diseases, in *Manganese in Soils and Plants,* Graham, R.D. et al. (eds.), Kluwer Academic Publishers, London, U.K., 154–173, 1988.

were lower at higher soil pH (Smiley et al., 1996). Table 7.3 shows the influence of soil pH and nitrogen form on plant diseases. Graham (1983) concluded that increasing fertilizer N may either increase or decrease disease, depending on other interacting factors, but in either case it will increase yield where the soil is deficient in the nutrient. Further, Graham (1983) concluded that N effects are associated with effects on the balance between the primary and secondary metabolic pathways in the host.

Various factors influence the effects that a specific form of N will have on disease. Because no one form of N controls all diseases or favors disease control on any group of plants, each disease must be considered individually. Disease control achieved with a specific form of N may depend on several factors, including host response, previous crop, nitrogen rate, residual N, time of application, soil microflora, ratio of NH_4^+–N to NO_3^-–N, and the disease complex present (Huber and Watson, 1974). A given form of N may reduce one disease but increase another, as observed with Verticillium wilt and Rhizoctonia canker of potato (Huber, 1989). An extensive list of diseases influenced by the different forms of N was presented by Huber (1991). This subject is very complex, and more research is needed to arrive at definite conclusions.

7.3 PHOSPHORUS

Although phosphorus (P) is involved in organic compounds and metabolic processes vitally important to the plant, its role in disease resistance is variable and seemingly inconsistent (Kiraly, 1976; Prabhu et al., 2007a). However, it has been widely reported that balanced and adequate fertility for any crop reduces plant stress, improves physiological resistance, and decreases disease risk (Krupinsky et al., 2002; Prabhu et al., 2007a). Application of P is most beneficial in reducing fungal diseases of seedlings, where vigorous root development permits plants to escape disease. Phosphate

TABLE 7.4
Influence of Phosphorus on Some Fungal Diseases in Principal Field Crops

Crop Species	Disease	Pathogen	Effect, Increase (I) or Decrease (D)
Sugarbeet	Rot	*Phom* spp.	D
Corn	Stalk rot	*Diplodia zeae*	I
Corn	Root rot	*Gibberella saubinetii*	D
Lentil	Wilt	*Fusarium oxysporum* f. sp. *lentis*	I
Pea	Damping-off	*Rhizoctonia solani*	D
Potato	Late blight	*Phytophthora infestans*	I, D
Rice	Stem rot	*Sclerotium oryzae*	I
Rice	Blast	*Pyricularia grisea*	I, D
Sorghum	Covered smut	*Sphacelotheca sorghi*	D
Soybean	Root rot	*Rhizoctonia solani*	D
Sugarcane	Rust	*Puccinia melanocephala*	D
Sugarcane	Eyespot	*Helminthosporium sacchari*	D
Wheat	Flag smut	*Urocystis tritici*	D
Wheat	Powder mildew	*Erysiphe graminis* f. sp. *tritici*	I, D
Wheat	Bunt	*Tilletia* spp.	I, D
Wheat	Take-all	*Gaeumannomyces graminis*	D
Wheat	Scab	*Gibberlla zeae*	I
Wheat	Root rot	*Helminthosporium sativum*	I, D

Source: Compiled from Prabhu, A.S. et al., Phosphorus and plant disease, in *Mineral Nutrition and Plant Disease,* Datnoff, L.E. et al. (eds.), The American Phytopathological Society, St. Paul, MN, 45–55, 2007a.

fertilization of wheat has almost eliminated economic losses from *Pythium* root rot in the central wheat growing area in the United States (Huber, 1980). Beneficial effects of P also occur with soil-borne diseases like take-all (*Gaeumannomyces graminis*) of wheat (Huber, 1981).

A survey of Illinois field research suggests that fertilizer P reduced corn cob rot caused by *Fusarium* where soils were deficient in P. Other studies reveal that P can diminish the incidence of boil smut of corn (Potash and Phosphate Institute, 1988). Application of P also reduced bacterial leaf blight on rice; downy mildew, blue mold, and leaf curl virus diseases in tobacco; pod and stem blight in soybean; yellow dwarf virus disease of barley; brown stripe disease in sugarcane; and blast disease in rice (Potash and Phosphate Institute, 1988). In contrast, applications of P may increase the severity of diseases caused by *Sclerotinia* on many garden plants, *Bremia* on lettuce, and flag smut on wheat (Huber, 1980). Influence of P on some fungal diseases of principal field crops is given in Table 7.4.

7.4 POTASSIUM

Although there is a large amount of literature on the relationship between potassium (K) and plant diseases, there is little quantitative information available on the concentration of K in soil or plant tissues that result in the observed effects on disease expression (Huber and Arny, 1985; Prabhu et al., 2007b). Generally, K fertilization reduces the intensity of several infectious diseases, and this occurs with diseases caused by obligate as well as facultative parasites (Kiraly, 1976; Prabhu et al., 2007b). It has been frequently observed that K reduces the incidence of, or damage from, various diseases such as bacterial leaf blight; sheath blight, stem rot, and sesamum leaf spot in rice; black rust in wheat; sugary disease in sorghum; bacterial leaf blight in cotton; *Cercospora* leaf spot in cassava; tikka leaf spot in peanut, red rust in tea, *Cercospora* leaf spot in mung bean (*Vigna radiata* L.); and seedling rot caused by *Rhizoctonia solani* in mung bean and cowpea (Tandon and Sekhon, 1989).

Perrenoud (1977) reviewed the relation between K fertilization and plant diseases in 534 references, and Usherwood (1980) drew the following conclusions from Perrenoud's review:

1. Potassium improved plant health in 65% of the studies and was deleterious 23% of the time.
2. Potassium reduced bacterial and fungal diseases 70% of the time, insects and mites 60% of the time, and the effects of nematodes and viruses in a majority of the cases.
3. Fungal disease infestation was reduced by K on an average of 48% in soils tested low in K and 14% where soil test levels were unknown.
4. The influence of K on crop yield varied according to the parasite group. The average increase in yield or growth was 48% for fungal diseases, 99% for viruses, 14% for insects and mites, and 70% for bacteria.
5. The mode of action is primarily through plant metabolism and morphology. The K-deficient plants have impaired protein synthesis and accumulate simple N compounds like amides that are good nutrient sources for invading pathogens. Tissue hardening and stomatal opening patterns are closely related to infestation intensity.
6. Crop response is not consistently different for sources of K.
7. The balance between N and K affects disease susceptibility of plants.
8. Benefits were noted more frequently in the field than in laboratory and greenhouse experiments.

The nature of the action of K in controlling the severity of plant diseases is still not understood. It may relate, in part, to the effect of K in promoting the development of thicker outer walls in epidermal cells, thus preventing disease attack. In addition, plant metabolism is much influenced by K, and some plant diseases may be favored by changes in metabolism associated with low K contents in the plant (Mengel and Kirkby, 1978).

Graham (1983) reported that in K-deficient plants, the loss of cell turger may be a physical factor facilitating penetration, both by fungi and insects. K-deficient plants accumulate soluble organic acids, amino acids, and amines. Glutamine, for example, is particularly high in K-deficient plants and has been shown to stimulate germination of spores of at least one fungal pathogen *Piricularia oryzae* on rice leaves (Graham, 1983). Effects of K on bacterial, viral, fungal, and nematode diseases are summarized in Table 7.5.

7.5 CALCIUM, MAGNESIUM, AND SULFUR

Calcium supplied as dolomitic lime to crops in acid soils is a dominant practice. Application of dolomitic lime in acid soils not only supplies Ca and Mg but also raises soil pH. This may have significant effect on plant growth and development and yields. Yields of legumes in most acid soils increase with liming (Fageria and Baligar, 2008). Hence, it is difficult to separate the dual effects of lime in providing Ca and Mg and in increasing pH. Rahman and Punja (2007) reported that in addition to agronomic benefits gained by maintaining adequate levels of Ca in plant species, the application of Ca to soils, foliage, and fruits reduced the incidence and severity of several diseases of economically important field crops.

Calcium has important roles in the integrity of all membranes and cell walls. These have been invoked as mechanisms for the resistance that Ca often confers against *Pythium*, *Sclerotium*, *Botrytis*, and *Fusarium* (Graham, 1983). Many physiological disorders of storage organs, fruits, certain vegetables, roots, and young enclosed leafy structures are related to the Ca content of the respective tissues. For example, adequate soil Ca is needed to protect peanut pods from diseases caused by *Rhizoctonia* and *Pythium*. Increasing the tissue content of Ca normally diminishes the occurrence of such diseases (Bangerth, 1979). Rahman and Punja (2007) reported that Ca application to soil reduces many diseases in principal food crops. These authors also concluded that

TABLE 7.5
Influence of Potassium on Bacteria, Fungal, Viral, and Nematode Diseases on Principal Field Crops

Crop Species	Disease	Pathogen	K Effect
Bacterial Diseases			
Bean, lima	Bacterial blight	*Pseudomonas syringae*	Decrease
Cassava	Bacterial blight	*Xanthomonas manihotis*	Decrease
Cotton	Angular leaf spot	*Xanthomonas malvacerarum*	Decrease
Potato	Scab	*Streptomyces scabies*	Increase
Rice	Bacterial blight	*Xanthomonas oryzae*	Decrease
Corn	Stewarts wilt	*Erwinia stewartii*	Decrease
Fungal Diseases			
Corn	Stalk rot	*Fusarium moniliforme*	Decrease
Alfalfa	Leaf spot	*Pseudopeziza medicaginis*	Decrease
Barley	Powdery mildew	*Erysiphe graminis*	Decrease
Dry bean or common bean	Leaf spot	*Mycosphaerella cruenta*	Increase
Dry bean or common bean	Root rot	*Rhizoctonia solani*	Increase
Wheat	Leaf rust	*Puccinia triticina*	Decrease
Wheat	Bunt	*Tilletia* spp.	Decrease
Wheat	Take-all	*Gaeumannomyces graminis*	Increase or decrease
Wheat	Powdery mildew	*Erysiphe graminis*	Decrease
Peanut	Pod rot	*Rhizoctonia solani*	Increase
Peanut	Leaf spot	*Mycosphaerella arachidis*	Decrease
Cotton	Leaf blight	*Cercospora gossypina*	Decrease
Cotton	Root rot	*Phymatotrichum omnivorum*	Decrease
Potato	Canker	*Rhizoctonia solani*	Decrease or increase
Potato	Late blight	*Phytophthora infestans*	Decrease
Rice	Sheath blight	*Corticium sasakii*	Decrease
Rice	Stem rot	*Leptosphaeria salvinii*	Decrease
Rice	Blast	*Pyricularia oryzae*	Decrease or increase
Soybean	Pod rot	*Diaporthe sojae*	Decrease
Soybean	Root rot	*Phytophthora megasperma*	Increase
Sugarcane	Eyespot	*Helminthosporium sacchari*	Decrease
Viral Diseases			
Barley	Barley yellow dwarf	Barley yellow dwarf virus	Decrease
Dry bean	Mosaic	Tobacco mosaic virus	Decrease
Cassava	Mosaic	Africancassava mosaic virus	None
Oat	Barley yellow dwarf	Barley yellow dwarf virus	Increase or none
Potato	Mosaic	Potato mosaic virus	Decrease
Soybean	Mosaic	Soybean mosaic virus	Increase
Pea	Leaf roll	Pea leafroll virus	Increase

(*continued*)

TABLE 7.5 (continued)
Influence of Potassium on Bacteria, Fungal, Viral, and Nematode Diseases on Principal Field Crops

Crop Species	Disease	Pathogen	K Effect
Nematode Diseases			
Lima bean	Root knot	*Meloidogyne incognita*	Decrease
Sugarbeet	Sugarbeet nematode	*Heterodera schachtii*	Decrease
Cotton	Root knot	*Meloidogyne incognita*	None
Rice	White tip	*Aphelenchoides oryzae*	Increase
Soybean	Root knot	*Meloidogyne incognita*	Increase
Soybean	Soybean cyst	*Heterodera glycines*	Increase

Source: Compiled from Prabhu, A.S. et al., Potassium and plant disease, in *Mineral Nutrition and Plant Disease,* Datnoff, L.E. et al. (eds.), The American Phytopathological Society, St. Paul, MN, 57–78, 2007b.

TABLE 7.6
Effects of Calcium on Plant Diseases[a]

Pathogen or Disease	Low Ca	High Ca
Erwinia phytophthora	***	*
Rhizoctonia solani	***	*
Sclerotium rolfsii	***	*
Botrytis cinerea	***	**
Fusarium oxsporum	***	*
Jonathan spot (nonparasitic)	***	**
Bitter pit (nonparasitic)	***	**

Source: Adapted from Kiraly, Z., *Fertilizer Use and Plant Health,* Bern, Switzerland, 1976.

[a] Disease severity: *, low; **, medium; ***, high.

application of Ca for the control of plant diseases would be well suited for certain crops, permitting a potential reduction in fungicide use and improving crop quality and yields. Table 7.6 shows the severity of some diseases at high and low levels of Ca.

Calcium often increases host resistance; however, in other cases, it renders the pathogen more virulent, thereby increasing the severity of disease symptoms. Hancock and Miller (1965) have shown that the Ca mobilized in lesions caused by *Colletotrichum trifolii* in alfalfa supports fungus growth by stimulating the macerating action of pectolytic enzyme, polygalacturonic acid transeliminase (Kiraly, 1976).

There is little information on the effects of S and Mg nutrition on plant diseases. The fungicidal effect of foliar-applied elemental S has been exploited since the end of the nineteenth century (Hoy, 1987; Haneklaus et al., 2007). In comparison, the significance of soil-applied S, independent of the form of S, for disease resistance only became evident a century later, when S deficiency developed into a widespread nutrient disorder (Haneklaus et al., 2007). Sulfur in the form of acidifying fertilizer is commonly applied to reduce soil pH and, consequently, the severity of potato scab, which is caused by *Streptomyces* bacteria (Huber, 1980). Fertilization with soil-applied S in sulfate form proved to have a significant effect on the infection rate and infection severity of fungal diseases in different crops (Klikocka et al., 2005). For example, there was a significant reduction in light leaf

spot of oilseed rape, caused by *Pyrenopeziza brassicae* and stem canker of potato, caused by *R. solani*. Soil-applied S reduced the rate and severity of infection of potato tubers *R. solani* by 41% and 29%, respectively (Klikocka et al., 2005).

Foliar-applied S had a fungicidal effect on *Pyrenopeziza brassicae* (Coleno, 1987). Elemental S has proved to be effective against rust and powdery mildew (Coleno, 1987; Cook, 1987; Hoy, 1987; Reuveni, 2001) and has also been successfully used against other diseases such as downy mildew of cereals (Hoy, 1987), common scab of potato, and alternaria black spot of oilseed rape (Haneklaus et al., 2007). Haneklaus et al. (2007) reported that the sequence, magnitude, and efficacy of individual S metabolites involved in the activation and strengthening of plant defenses by S fertilization are not known; these could be released in a chain reaction triggered by the pathogen and mediated by the S status of the plant. The free cysteine pool is one of the factors related to resistance (Vidhyasekaran, 2000), and nonprotein cysteine is a precusor of all of the relevant S-containing metabolites putatively involved in sulfur-induced resistance (Haneklaus et al., 2007).

Magnesium decreases the Ca content of peanut pods and may predispose them to pod breakdown by *Rhizoctonia* and *Pythium*. Jones and Huber (2007) reported that Mg can increase tissue tolerance to maceration by pectolytic enzymes produced by soft rot bacteria, but apart from this, there is little information on direct effects of Mg on pathogenesis.

7.6 MICRONUTRIENTS

The essential micronutrients for crop plants are Zn, Fe, Mn, Cu, B, Mo, Cl, and Ni. In some publications, Co is also cited as an essential micronutrient; however, essentiality of this element is not proved for crop plants (Fageria et al., 2002). Deficiency of micronutrients in annual crops has been reported in many parts of the world (Alloway, 2008; Fageria and Stone, 2008; Graham, 2008). Alloway (2008) reported that this is largely due to the increased intensification of arable farming in many parts of the world and also to the cultivation of virgin and/or reclaimed land. Intensification involves the increased use of N, P, and K and other fertilizers, growing new and higher yielding crop cultivars, liming to create optimal soil pH for crop growth and increased use of irrigation. Prior to this intensification, much lower crop yields were usually accepted as the norm in many parts of the world, and the crop cultivars grown were generally well adapted to local soil and climatic conditions (Alloway, 2008).

Influence of macronutrients on crop diseases has received considerable attention over the years, but very little attention has been paid to micronutrients. In addition, little systematic research has been done under field conditions on the effects of micronutrients on crop diseases. This section reviews some of the available information about the roles of Zn, B, Mn, Cu, Fe, and Ni nutrition in plant diseases. In addition, the roles of the beneficial element Si and the toxic element Al in defense mechanisms of plants for disease resistance are also discussed. Furthermore, the effects of organic manures and salt-affected soils in controlling plant diseases are also discussed.

7.6.1 Zinc

Zinc deficiency is widespread in various parts of the world as a result of intensive cropping, loss of top soil by erosion, losses of micronutrients through leaching, liming of acid soils, decreasing application of farmyard manure, increased purity of chemical fertilizers, and high nutrient demands of modern crop cultivars (Fageria and Stone, 2008).

The role of Zn in the defense mechanisms of higher plants is far from clear. There are reports of beneficial effects, no effects, and negative effects of Zn application on plant diseases. Zinc application often increases host resistance to mildew and leaf spot and has suppressive effects on soilborne diseases and bacterial and viral diseases (Graham, 1983). With Zn deficiency, a leakage of sugars onto the leaf surface of *Hevea brazilensis* increased the severity of infection with *Oidium* (Bolle-Jones and Hilton, 1956). According to Graham (1983), Zn deficiency inhibits protein synthesis and

TABLE 7.7
Influence of Zinc on Plant Diseases

Crop Species	Disease	Pathogen	Effect of Zn
Wheat	Rhizoctonia root rot	*Rhizoctonia solani*	Reduces
Wheat	Take-all	*Gaeumanomyces graminis*	Reduces
Wheat	Mildew	*Erysiphe graminis*	Increases
Wheat	Crown and root rot	*Fusarium graminearum*	Reduces
Cowpea	Rhizoctonia root rot	*Rhizoctonia solani*	Reduces
Alfalfa	Rhizoctonia root rot	*Rhizoctonia solani*	Reduces
Alfalfa	Phytophthora root rot	*Phytophthora megaspera*	Reduces
Alfalfa	Common leaf spot	*Pseudopeziza medicaginis*	Reduces
Corn	Smut	*Ustilago maydis*	Reduces
Potato	Common scab	*Streptomyces scabies*	Negligible effect
Potato	Powdery scab	*Spongospora subteranea*	Reduces
Dry bean	Mosaic	*Mosaic virus*	Reduces
Clover	Mosaic	*Mosaic virus*	Reduces

Source: Compiled from Duffy, B., Zinc and plant disease, in *Mineral Nutrition and Plant Disease*, Datnoff, L.E. et al. (eds.), The American Phytopathological Society, St. Paul, MN, 155–177, 2007.

produces high concentrations of nonprotein N, including amino acids. Such accumulations may favor invading heterotrophs.

Zinc consistently stimulates germination of fungal spores (Graham, 1983), but whether this effect is significant in pathogenesis is not well known. Stimulation of plant disease infestations by Zn application may be related to its antagonism of Mn and Cu uptake. These two elements generally increase plant resistance to diseases, as discussed later in this section. Table 7.7 presents the effects of zinc on crop diseases.

7.6.2 Boron

Boron (B) has been used as a fertilizer for more than 400 years, but it was not shown to be an essential element until the twentieth century (Mengel and Kirkby, 1978). Boron deficiency is widespread and has been reported in at least 80 countries on 132 crop species (Shorrocks, 1997). Fageria et al. (2007) conducted a field experiment with upland rice and common bean grown in rotation on a Brazilian Oxisol. Upland rice did not respond to B applications but the yield of common bean was significantly increased with B fertilization. Maximum grain yield was achieved at about 2 kg B ha^{-1}. Dicotyledonous plants require higher tissue B concentrations than monocots, a difference apparently related to the greater production of secondary metabolites in the former (Graham, 1983). Stangoulis and Reid (2002) reported that cereals are sensitive to B toxicity because of their low B requirements.

The suppression of disease by B fertilizers has been well reported in the literature (Gupta and Singh 1995; Kumar and Sharma, 1997; Sarkar et al., 2000; Stangoulis and Graham, 2007). However, greater susceptibility to disease in B-deficient plants has been reported at least as frequently in monocots as in dicots. The rate of powdery mildew infection was sevenfold higher in B-deficient wheat plants than in those with sufficient B, and the fungus also spread more rapidly over the plant (Schutte, 1967). Perhaps, one of the most spectacular effects of added B is the reduction of the pathogenic fungus *Plasmodiophora brassicae* Woronin in *Brassica* species (Dixon, 1996; Stangoulis et al., 2007). Graham and Webb (1991) proposed that B retards the movement of fungal hyphae through the cortex. Stangoulis et al. (2007) reported that B plays a significant role in lignification and phenol metabolism, which are intrinsically associated with plant defense systems.

7.6.3 Manganese

The availability of manganese (Mn) in soil is extremely complex and depends on factors such as pH, moisture, nutrients, chloride, nitrification inhibitors, organic matter, and microbial activity (Graham, 1983; Ghiorse, 1988; Fageria et al., 2002). Soil pH affects solubility, adsorption, desorption, oxidation of Mn, and reduction of Mn oxides in soil. As pH decreases, Mn is mobilized from various fractions and increases Mn soil solution concentrations and availability. Exchangeable (plant available) Mn was high at low soil pH (<5.2), while organic and Fe oxide fractions of Mn (low availability) were high at high pH (Sims, 1986). In sandy soil, increasing pH also increased organic fractions of Mn (Shuman, 1991). Increasing soil pH with Mg applications decreased Mn toxicity and leaf and stem Mn concentrations in peanuts (Davis, 1996). Reduction of Mn^{4+} to Mn^{2+} is greatest at low soil pH, and acid soil conditions (<pH 5) lead to Mn toxicities for many sensitive plant species (Mortvedt, 2000). In addition, high molecular weight organic colloids decrease as soil pH increases, reducing the adsorption of Mn, as well as Cu and Fe (Geering and Hodgson, 1969). Soil solution Mn increased 1.6-fold for each unit decrease in pH in a well-drained Mollisol acidified with high rates of N fertilizer, indicating that soil acidity and aeration are important for Mn availability (Fageria et al., 2002). Manganese deficiency in South American soils is mainly due to soil erosion and liming acid soils to raise pH and base saturation (Fageria and Stone, 2008).

Manganese is a crucial nutrient in host resistance to disease and in disease interactions (Thompson and Huber, 2007). The Mn concentration in plant tissue is altered by many diseases caused by fungi (Huber and McCay-Buis, 1993; Thompson and Huber, 2007), bacteria (Evans et al., 2001), viruses (Chandra and Monday, 1981), parasitic plants (Ehleringer and Schulze, 1985), and nematodes (Nasr et al., 1980). Manganese concentrations are usually lower in tissues susceptible to fungal, viral, and bacterial pathogens than in resistant tissues (Kudelova et al., 1978; Cordrey and Bergman, 1979; Anderson and Dean, 1986). Huber and Wilhelm (1988) reviewed the effects of Mn on plant diseases and concluded that out of 62 references, 85% reported decreases in fungal, bacterial, and viral diseases with Mn application. The greater resistance of paddy-grown rice to blast (*P. oryzae*) compared with upland rice has been attributed to the increased uptake of Mn by flooded rice under reduced soil where Mn^{2+} concentrations may even increase to toxic levels (Chou and Chiou, 1979). Similarly, Thompson and Huber (2007) reported that environmental conditions increasing Mn availability reduces rice blast and conditions reducing Mn availability increase the disease. These authors also reported that rice blast caused by *Magnaporthe grisea* is a very strong Mn oxidizer (reducing Mn availability), and oxidized Mn can be detected around an infection site shortly after appressorium formation and prior to penetration. Infected tissues accumulate insoluble oxidized Mn, while uninfected tissues contain reduced, physiologically available Mn (Thompson and Huber, 2007). Breeding Mn-resistant crop cultivars is a very vital, economically and environmentally sound strategy to improve disease resistance (Graham and Webb, 1991; Thompson and Huber, 2007).

Similarly, brown spot (*Helminthosporium oryzae*) on rice is severe on Mn-deficient soils irrespective of pH. Kaur and Padmanabhan (1974) reported that application of Mn to soil or water decreased the severity of brown spot in highly susceptible rice varieties, and even resistant varieties became susceptible when the Mn concentration in host tissue dropped below 2.5 mg kg^{-1}. Several mechanisms may be involved in the relationship between Mn and disease, including a direct effect of Mn on pathogen toxicity or virulence, modification of host plant resistance, an influence of pathogens on Mn availability, or a combination of these effects (Huber, 1980, 1981; Graham, 1983; Huber and Wilhelm, 1988). Table 7.8 shows the effects of Mn on plant diseases.

7.6.4 Copper

Factors that influence the level of available copper (Cu) in soil are organic matter, clay type and content, oxide type and content, redox potential, and microorganisms and nature of other elements associated with Cu (Fageria et al., 2002). Copper uptake is metabolically mediated and strongly inhibited by

TABLE 7.8
Reported Effects of Manganese on Plant Diseases

Host Plant	Disease	Pathogen	Effect of Mn
Barley	Aphid	*Rhopalosiphum maidis*	Decrease
Barley	Leaf spot	*Helminthosporium*	Increase
Barley	Mildew	*Erysiphe graminis*	Decrease
Barley	Mildew	*Erysiphe graminis*	Increase
Bean	Virus	Tobacco mosaic virus	Decrease
Cotton	Damping-off	*Rhizoctonia solani*	Decrease
Cotton	Wilt	*Fusarium oxysporium*	Decrease
Cotton	Wilt	*Verticillium alboatrum*	Decrease
Cowpea	Mildew	*Erysiphe polygone*	Decrease
Cowpea	Virus	Chlorotic mottle virus	Increase
Lentil	Wilt	*Fusarium oysporium*	Decrease
Oats	Bacterial blight	*Pseudomonas* spp.	Decrease
Onion	Rot	Storage fungi	Decrease
Pigeonpea	Wilt	*Fusarium udum*	Decrease
Potato	Late blight	*Phytophthora infestans*	Decrease
Potato	Stem canker	*Rhizoctonia solani*	Decrease
Potato	Scab	*Streptomyces scabies*	Decrease
Potato	Wilt	*Verticillium dahliae*	Decrease
Rice	Bacterial blight	*Xanthomonas oryzae*	Decrease
Rice	Bacterial blight	*Xanthomonas oryzae*	Increase
Rice	Blast	*Pyricularia oryzae*	Decrease
Rice	Brown spot	*Helminthsporium oryzae*	Decrease
Rice	Leaf spot	*Helminthsporium sigmoidum*	Decrease
Sorghum	Downy mildew	*Peronosclerospora sorghi*	Decrease
Soybean	Blight	*Pseudomonas glycinea*	Decrease
Sugarbeet	Leaf spot	*Cercospora* spp.	Decrease
Sugarbeet	Insect	Root borer	Decrease
Sugarcane	Whip smut	*Ustilago scitaminca*	Decrease
Sweet potato	Root rot	*Streptomyces ipomoea*	Decrease
Wheat	Mildew	*Erysiphe graminis*	Decrease
Wheat	Rust	*Puccinia* spp.	Decrease

Source: Compiled from various sources by Huber, D.M. and Wilhelm, N.S., The role of manganese in resistance to plant disease, in *Manganese in Soils and Plants,* Graham, R.D. et al. (eds.), Kluwer Academic Publishers, London, U.K., 154–173, 1988.

other divalent transition metals, especially Zn (Fageria, 2009). Applications of relatively high levels of N and P fertilizers have induced Cu deficiency on plants grown in low-Cu soils. Even though N and Cu interact, no significant effects of NO_3–N or NH_4–N on Cu uptake have been noted (Kochian, 1991). Even though increased soil P induced Cu deficiency, this response was related to dilution effects from increased growth and depressing effects of P on Cu absorption (Fageria et al., 2002). Copper toxicity has also been noted in P-deficient plants (Wallace, 1984). Plants grown in coarse textured soils with low available P and Fe and high in Cu had induced Cu toxicity (Moraghan and Mascagni, 1991).

Copper has been used as a fungicide for more than a century. Copper oxychloride and various Bordeaux mixtures (consisting of copper sulfate, lime, and water) have long been used for the control of fungal diseases. The use of Bordeaux mixture in New Zealand in the nineteenth century to control late blight of potatoes caused by *Phytophthora infestans* led to the discovery of Cu

as an essential micronutrient for plant growth (Evans et al., 2007). It has now become clear that Cu-deficient plants are frequently more susceptible to airborne fungal diseases than plants with adequate Cu (Evans et al., 2007). A number of other diseases have been reported to be more severe on Cu-deficient plants, such as *Alternaria* on sunflower, *G. graminis* on wheat, *Claviceps pururea* on rye and barley, *Heterodera* on sugar beet, *Puccinia tritica* on wheat, *P. oryzae* on rice, and *Sclerotinia* on peanuts (Graham, 1983). Poor lignification, impaired phenol metabolism, accumulation of soluble carbohydrates, and delay in leaf senescence are probably the main reasons for the higher susceptibility of Cu-deficient plants (Marschner, 1995).

Use of Cu fertilizers in crop plants may provide effective control of many diseases by stimulating plant defense mechanisms. Adequate levels of Cu in the soil–plant systems may act as a bactericide or fungicide to control disease pathogens. However, Evans et al. (2007) reported that effects on plant resistance and pathogen virulence are also involved, and several mechanisms may operate simultaneously. Many authors have reported (Graham, 1983; Graham and Webb, 1991; Evans et al., 2007) that Cu is a regulator of or an essential cofactor in various enzyme systems involved in plant defense against infection, the production of antimicrobial compounds, and general disease resistance. For example, copper chloride induces the activity of chalcone synthetase, a key enzyme in the biosynthesis of diverse flavonoids involved in plant disease resistance (Harker et al., 1990; Evans et al., 2007). A Cu-binding blue protein has been found to be involved in upregulating the expression of disease resistance genes (Yang et al., 2002). Table 7.9 shows effects of Cu in disease control of principal food crops.

TABLE 7.9
Influence of Copper on Diseases of Principal Food Crops

Crop Species	Disease	Pathogen	Cu Effect
Dry bean	Halo blight	*Pseudomonas phaseolicola*	Decrease
Dry bean	Anthracnose	*Colletotrichum lindemuthaianum*	Increase
Rice	Bacterial blight	*Xanthomonas oryzae*	Decrease
Rice	Sheath rot	*Sarocladium oryzae*	Decrease
Rice	Blast	*Magnaporthe grisea*	Decrease
Canola (rape)	Damping-off	*Rhizoctonia solani*	Increase
Canola (rape)	Brown root rot	*Rhizoctonia solani*	Increase
Cotton	Wilt	*Verticillium alboatrum*	Decrease
Cotton	Wilt	*Verticillium dahliae*	Decrease
Pea	Leaf spot	*Ascochyta rabiei*	Decrease
Pea	Root rot	*Aphanomyces cochlioides*	Decrease
Pea	Root rot	*Aphanomyces euteiches*	Decrease
Potato	Early blight	*Alternaria solani*	Decrease
Potato	Late blight	*Phytophthora infestans*	Decrease
Potato	Stem canker	*Rhizoctonia solani*	Decrease
Sorghum	Covered smut	*Sphacelotheca sorghi*	Decrease
Sugarcane	Rust	*Puccinia melanocephala*	Decrease
Barley	Take-all	*Gaeumannomyces graminis*	Decrease
Wheat	Ergot	*Claviceps purpurea*	Decrease
Wheat	Leaf rust	*Puccinia recondita*	Increase
Wheat	Stripe rust	*Puccinia striiformis*	Decrease
Wheat	Take-all	*Gaeumannomyces graminis*	Decrease
Wheat	Wet smut	*Ustilago tritici*	Decrease

Source: Compiled from Evans, I. et al., Copper and plant disease, in *Mineral Nutrition and Plant Disease*, Datnoff, L.E. et al. (eds.), The American Phytopathological Society, St. Paul, MN, 177–188, 2007.

7.6.5 Iron

Iron (Fe) deficiency is a worldwide problem and occurs in numerous crops (Fageria et al., 1990; Marschner, 1995; Fageria and Stone, 2008). Iron deficiency in plants is characterized by interveinal chlorosis in younger leaves (Fageria, 2009). In Brazil, Fe deficiency has been observed in upland rice, soybean, and sorghum grown on Oxisols. Iron deficiency in these crops occurs not because of low Fe concentrations in soil but because of various soil and plant factors that affect Fe availability and inhibit its absorption or impair its metabolic utilization (Marschner, 1995; Fageria et al., 2002; Fageria and Stone, 2008). Availability of Fe is reduced by high soil pH (>6.0), high P, high levels of Zn, Cu, and Mn, low and high temperatures, high levels of nitrate N, high organic matter content, poor aeration, unbalanced cation ratios, and root infection by nematodes (Fageria et al., 1990; Fageria and Stone, 2008; Fageria, 2009). Hansen et al., (2003) reported that Fe chlorosis in soybean was associated with a greater soil moisture content, high concentrations of soluble salts, and high carbonate contents, and that chlorotic tissues had lower concentrations of DTPA-extractable Fe and Mn than nonchlorotic areas. In Fe-deficient soils, foliar application of Fe increases the resistance of apples and pears to *Spaeropsis inalorum*, wheat to smut, and turf grass to *Fusarium* patch diseases. Wallace and North (1962) reported that Fe amendments can either correct or mask some virus symptoms in camellia. Increased Fe supply results in tolerance of cabbage to *Olpidium brassicae*.

Recent papers on siderophore production by bacteria in the soil reflect a new level of understanding about the involvement of Fe in plant disease resistance (Expert, 2007). As an element of competition in plant defense, iron could induce mechanisms causing pathogens to be deprived of nutritional iron (Expert, 2007). Competition between host and pathogen for Fe is considered to be an important defense mechanism in animals, and plant pathologists are looking for similar systems in the plant kingdom (Graham, 1983). The fluorescent pseudomonads are a group of agriculturally important Gram-negative, rod-shaped bacteria that are present in greater numbers in soils suppressive of "take-all" disease of wheat (Graham, 1983). According to Graham (1983), the fluorescent pseudomonads suppress disease by producing siderophores in the soil to compete with rhizosphere pathogens for Fe.

7.6.6 Chlorine

Among the earth's natural elements, chlorine (Cl) is the 18th most abundant element (Sawyer et al., 2000; Elmer, 2007). However, deficiencies of this element have been reported in many crops (Fixen, 1993; Engel et al., 1997; Elmer, 2007). Many studies indicate that the benefits of chloride application can be maximized when plants are under stress due to disease or drought (Trolldenier, 1985). Application of fertilizer containing Cl in Cl-deficient soils can also suppress plant diseases (Christensen and Brett, 1985; Elmer, 1992, 1995, 1997, 2007). Suppression of take-all root rot of wheat caused by the fungus *G. graminis* var. *tritici* is maximized when Cl is applied in conjunction with other management practices to reduce disease severity, for example, the use of ammonium N (NH_4^+–N), band-applied P, moderate soil acidity, and delayed planting (Taylor et al., 1983). Christensen et al. (1981) reported that the susceptibility of winter wheat plants to take-all fungus colonization may be reduced by lowering the chemical potential of water in the plant. Because the osmotic potential in wheat plants changes readily with Cl application, fertilization with Cl salts provides an opportunity to actively manage plant water potential to suppress take-all root rot.

Fixen (1987) reported that one of the most frequently reported effects of Cl fertilization is disease suppression (Table 7.10). To date, at least 15 different foliar and root diseases of 10 different crops have been significantly reduced in severity with the addition of Cl (Elmer, 2007). Researchers in Oregon and North Dakota say that the yield increases in their states are completely due to suppression of root rot.

Researchers in Oregon theorize that Cl acts as a nitrification inhibitor, forcing wheat plants to take up more nitrogen as ammonium than as nitrate when ammoniacal fertilizers are applied.

TABLE 7.10
Diseases Suppressed by Chloride Fertilizers

Location	Crop	Suppressed Disease
Oregon	Winter wheat	Take-all
Germany	Winter wheat	Take-all
North Dakota	Winter wheat	Tanspot
Oregon	Winter wheat	Stripe rust
Great Britain	Winter wheat	Stripe rust
South Dakota	Spring wheat	Leaf rust
South Dakota	Spring wheat	Tanspot
South Dakota	Spring wheat	Septoria
North Dakota	Barley	Common root rot
North Dakota	Barley	Spot blotch
Montana	Barley	Fusarium root rot
North Dakota	Durum	Common root rot
New York	Corn	Stalk rot
India	Pearl millet	Downy mildew
The Philippines	Coconut palm	Gray leaf spot
Oregon	Potatoes	Hollow heart
Oregon	Potatoes	Brown center
California	Celery	Fusarium yellows

Source: Adapted from Fixen, P.E., *Crops Soils Mag.,* 39, 14, 1987.

This, in turn, causes plant roots to excrete hydrogen ions, which increases the acidity at the root surface. The take-all fungus is inhibited by microorganisms that thrive in the more acidic root zone, and disease severity decreases. The effect of Cl is negligible if soil pH is above approximately 6.1 (Fixen, 1987). In addition, in acid soils, addition of Cl causes an increase of soluble Mn ions (Krishinamurti and Huang, 1992), and increased soluble Mn has been associated with disease suppression (Thompson and Huber, 2007). The effects of Cl addition on suppression of common root rot in barley have been explained via a slightly different mechanism. Chloride fertilization decreases nitrate concentrations in the plant, due to either nitrification inhibition as discussed with take-all or to general competition between chloride and nitrate for uptake. It is believed that plants with low nitrate concentrations are less likely to develop severe cases of common root rot (Fixen, 1987).

7.6.7 Nickel

Nickel (Ni) is the last of the 17 elements discovered to be essential for plant growth. During the 1980s, Welch and his associates at the U.S. Department of Agriculture demonstrated that Ni is essential to legumes (Welch, 1981; Eskew et al., 1983, 1984). In 1987, Ni was found to be essential in temperate cereal crops, and it was concluded that Ni is essential for all higher plants (Brown et al., 1987, 1990). In 1992, the Agriculture Research Service of United States added Ni to its list of essential plant nutrient elements (Wood and Reilly, 2007). However, Ni deficiency in crop plants is rarely observed.

The role of Ni in disease control is discussed by Wood and Reilly (2007). Rust fungi have long been known to be sensitive to Ni (Graham, 1983). Nickel salts have been used as a component of fungicides and have been observed to be effective when applied to foliage or to soil (Wood and Reilly, 2007).

Graham (1983) observed that soil-applied Ni exhibits both eradicative and protective activity against rusts, suggesting a physiological role in host resistance. Additionally, Ni inhibits the germination of rust spores (Mishra and Kar, 1974). Similarly, hyperaccumulation of Ni in a Brassicaceae species inhibited infection by certain pathogenic fungi and bacteria (Boyd et al., 1994). Additionally, it was observed that the ability of *Alyssum* seedlings to resist infection by *Pythium* spp. is linked to the amount of Ni in their seeds (Ghaderian et al., 2000). Nickel salts are especially effective in diseases caused by rust fungi (Kishore et al., 2001) and nematodes (Khan and Salam, 1990). Nickel has direct or indirect effects on pathogenic microorganisms, including viruses (Pennazio and Roggero, 1988), bacteria (Wang et al., 2000), and fungi (Singh et al., 1992). Direct inhibition of microbes by aqueous Ni spray usually occurs at concentrations greater than 200 mg L^{-1} (Wood and Reilly, 2007).

7.6.8 Silicon

Silicon (Si) is the most abundant element in the lithosphere after oxygen, and soil contains approximately 32% Si by weight (Lindsay, 1979). In the pH range 2–9, Si is available to plants as the monosilicic acid $Si(OH)_4$. Above pH 9, it occurs as the silicate ion. The availability of Si to plants, however, depends largely on how rapidly weathering takes place, bringing Si into soil solution. Silicon concentration in higher plant species varies from 1% to more than 10% of tissue dry weight (Epstein, 1991). Monocots typically accumulate more Si in their tissues than dicots (Datnoff et al., 2007).

Although Si is not considered an essential nutrient for plant growth, its beneficial effects in crop plants is well documented (Datnoff et al., 2001, 2007). Silicon provides lodging and drought resistance to crop plants (Epstein, 1991; Savant et al., 1997). In addition, Si can have positive influence on some enzymes involved in photosynthesis and leaf senescence (Kang, 1980; Savant et al., 1997). Silicon increases the oxidation power of rice roots in flooded soils (Datnoff et al., 2007) by increasing Fe^{2+} precipitation on root surfaces, thereby reducing Fe toxicity (Fageria et al., 2008).

In certain organic Histosols of the Florida Everglades low in plant-available Si, silicon fertilization has been shown to be beneficial to rice (Snyder et al., 1986; Deren et al., 1992). When these soils are amended with Si as calcium silicate slag, rice yields increased significantly, due in part to a reduction in disease severity (Datnoff et al., 1991). By the addition of plant-available Si to Si-deficient soils, diseases such as brown spot (*Bipolaris oryzae*) and blast (*Pyricularia grisea*) are greatly reduced (Yamauchi and Winslow, 1987).

Another possible effect of Si on rice grown on Everglades Histosols may be that it counteracts some of the detrimental effects of N, which, because of mineralization of soil organic N, is nonlimiting for rice, sugarcane, and other crops grown on these soils. High rates of N fertilization are associated with droopy leaves, lodging, generally poor plant architecture, and increased disease (Tisdale et al., 1985). Silicon applications have been observed to improve rice plant architecture and increase photosynthesis (Ishizuka, 1971). Although the mechanisms by which Si increases yield and disease tolerance are not well understood, clearly there is benefit in increasing plant silicon concentration on low-Si organic soils.

In West and Central Africa, rice is often grown on freely drained upland soils in high-rainfall forest areas. The highly weathered Ultisols and Oxisols have lost most of their Si, and probably have insufficient Si to satisfy the requirements of the crop (Winslow, 1992). Application of Si to an upland Ultisol soil at Onne, Nigeria increased rice yields and reduced damage from diseases (Yamauchi and Winslow, 1989). The association between Si deficiency and diseases raises the possibility of increasing disease resistance by breeding cultivars with higher Si contents. Some authors report higher blast resistance in high-Si genotypes (Deren et al., 1992; Winslow, 1992). Datnoff et al. (2007) reported that Si application at the rate of 0.4 Mg ha^{-1} increased yield as much as applying the fungicide benomyl at the labeled rate.

Deren et al. (1994) reported that rice genotypes differed in Si concentration and disease severity at several locations and Si fertilizer treatments. Among genotypes, disease severity was negatively correlated with Si concentration in plant tissue. Increases in yield with added Si were attributable to a greater numbers of grains per panicle, whereas weight per 100 seed and panicles per square meter were less affected.

TABLE 7.11
Influence of Silicon on Plant Diseases of Principal Food Crops

Crop Species	Disease	Pathogen	Effect of Si
Barley	Powdery mildew	*Erysiphe graminis* f. sp. hordei	Decreases
Barley	Black point	*Alternaria* spp.	Decreases
Corn	Stalk rot	*Pythium aphanidermatum*, *Fusarium moniliforme*	Decreases
Rice	Blast	*Magnaporthe grisea*	Decreases
Rice	Brown spot	*Cochliobolus miyabeanus*	Decreases
Rice	Sheath blight	*Thanatephorus cucumeris*	Decreases
Rice	Leaf scald	*Monographella albescens*	Decreases
Rice	Stem rot	*Magnaporthe salvinii*	Decreases
Rice	Grain discoloration	Many fungal species	Decreases
Sorghum	Anthracnose	*Colletotrichum graminicola*	Decreases
Sugarcane	Rust	*Puccinia melanocephala*	No effect
Wheat	Powdery mildew	*Blumeria graminis*	Decreases
Wheat	Brown rust	*Puccinia recondita*	No effect
Wheat	Foot rot	*Fusarium* spp.	Decreases
Wheat	Leaf spot	*Phaeosphaeria nodorum*	Decreases
Pea	Leaf spot	*Mycosphaerella pinodes*	Decreases
Soybean	Stem canker	*Diaporthe phaseolorum*	Decreases

Source: Compiled from Datnoff, L.E. et al., Silicon and plant disease, in *Mineral Nutrition and Plant Disease*, Datnoff, L.E. et al. (eds.), The American Phytopathological Society, St. Paul, MN, 233–246, 2007.

Poor silicification of rice epidermal cells increases susceptibility to such fungal diseases as rice blast and *Helminthosporium* leaf spot. Many workers feel that silicates in the leaf epidermal layer prevent physical penetration of fungi (Ou, 1972; Graham, 1983). For healthy growth, the SiO_2/N ratio should be wide (Matsubayashi et al., 1963). Plants given large amounts of N are found to have less-silicated epidermal cells and, thus, lower blast resistance (Ou, 1972). Silicification of cell walls is also linked with K nutrition. According to Nogushi and Sugawara (1966), K deficiency reduces the accumulation of SiO_2 in the cells of the leaf blades, thus increasing the susceptibility to rice blast. Wheat and barley powerdy mildew was effectively controlled with the application of Si (Graham, 1983; Rodgers-Gray and Shaw, 2004). Data in Table 7.11 show that many diseases can be controlled with the addition of Si.

7.6.9 Aluminum

A large part of the agricultural lands of the world are acidic and cause aluminum (Al) toxicity in susceptible crops. High concentration of Al^{3+} in acid soils has adverse effects on plants root growth, which affects uptake of water and nutrients. The most effective methods of ameliorating Al toxicity in acid soils is liming (Fageria and Baligar, 2008). Although Al is not essential for plant growth, in some crops low concentrations of soluble Al in soils can improve plant growth. The beneficial effects of low levels of Al^{3+} (10 mg L^{-1}) have been observed by Fageria (2009) in rice plants grown in solution culture. The growth of rice roots and shoot was better at 10 mg Al L^{-1} than when no Al was present in the nutrient solution (Fageria, 2009).

The chemistry of Al in acid soils has been extensively studied (Foy, 1988; Menzies, 2003; Fageria and Baligar, 2008). However, the influence of Al on plant diseases is not well understood, although Al is known to suppress the growth of some fungi (Shew et al., 2007), and the control of bacterial and fungal root diseases by soil acidification is well established (Shew et al., 2007). Some evidence suggests that Al

ions may enhance the production of phytoalexins (Jeandet et al., 2000; Shew et al., 2007). Shew et al. (2007) speculates that it may be beneficial to apply Al to the shoots of plants in addition to using it as a soil amendment. This could both control leaf pathogens directly and stimulate plant defenses.

7.6.10 Organic Manures

The value of plant nutrition in reducing the incidence and severity of plant pathogens has been recognized for many years. Although most metabolic or physiological mechanisms involved in host–pathogen interactions are not clearly understood, specific nutrients are known to reduce disease severity by affecting virulence of the pathogen, enhancing resistance of the plant, compensating for pathogenic damage, or activating indigenous biological control mechanisms. The source of nutrients may be either inorganic or organic, and nutrients from either source generally have comparable effects. However, organic sources, as complex mixtures of nutrients, may have much more complex effects on disease incidence and severity than inorganic sources (Huber, 1981).

Huber and Watson (1970) concluded that organic amendments and crop rotations probably influence the severity of soilborne diseases by (1) increasing the biological buffering capacity of the soil, (2) reducing pathogen numbers during anaerobic decomposition of organic matter, (3) affecting nitrification, which influences the forms of inorganic nitrogen in the soil, and (4) denying the pathogen a host. The specific forms of nitrogen available to the plant and soil microflora, in turn, influence microbial associations and host physiology. Crop residues and animal manures can provide an environment where pathogens can flourish. For example, farmyard manure can increase *Rhizobium solani* disease incidence in cotton and cowpea seedlings (Bandyopadhyay et al., 1982). Kataria and Grover (1987) reported that both farmyard manure and green manure aggravated mung bean seedling rot by *R. solani*. Crop residues in conservation tillage can support higher pathogen and insect populations and thus prompt increased pesticide use (Sojka et al., 1991). Weeks (1993) applied crop residues (peanut hay and peanut hulls) to soils contaminated with heavy metals to increase adsorption of the metals and reduce their uptake by peanut, but spring hay application increased late leafspot disease scores. Organic amendments to soil have many positive effects; however, they can also increase disease incidence, thus increasing the need for pesticide application (Davis, 1994).

7.6.11 Plant Diseases and Salt-Affected Soils

Little information is available on the effects of soil salinity and sodicity on plant diseases. The effects of soil salts on plant growth are physiological, whether nutritional, osmotic, or directly toxic (Bernstein, 1975). No direct effects of soil salinity or sodicity on pathogens are known, but some indirect effects have been observed. Generally, saline soils have higher moisture contents than nonsaline soils under given meteorological conditions (Bernstein, 1975). Wet soil conditions may favor *Phytophthora* root rot and other fungal infections (Bernstein and Francois, 1973). None of these diseases is specifically salinity induced. Improving the water regime by better irrigation or drainage may prevent the fungus diseases associated with wetter soil conditions, even without a decrease in soil salinity (Bernstein, 1975).

7.7 SUMMARY

Production losses caused by crop diseases are considerable, and nutrition plays an important role in determining plant resistance or susceptibility to diseases. In this chapter, relationships between essential nutrients and plant diseases have been reviewed, and the following conclusions can be drawn:

1. A well-nourished crop plant is generally more tolerant of disease than one with suboptimum nutrition.
2. The severity of most diseases can be reduced by improved management of mineral nutrition.

3. Nitrogen differently affects diseases caused by obligate and facultative pathogens. High N fertilization increases susceptibility of host plants to obligate pathogens, but it decreases their susceptibility to facultative pathogens. Application of K, Ca, Mn, Fe, B, Cu, and Si to deficient soils usually increases resistance. The effects of P and Zn are variable. There is not sufficient information on Mg and S to reach definite conclusions. Potassium acts on a number of processes that include alterations in protein or amino acid availability, decreased cell permeability, or decreased susceptibility of tissue to maceration and penetration. Silicon affects plant disease resistance by either an accumulation of absorbed silicon in the epidermal tissue, or expression of pathogenesis-induced host defense responses. Chloride appears to reduce the cell osmotic potential, increase Mn uptake, and enhance the activity of beneficial microbes via altered root exudation.
4. Macronutrients increase resistance to disease, if at all, only in the deficiency range. Very high tissue concentrations of nutrients do not provide further protection and, in some cases, may be detrimental.
5. Correction of a micronutrient deficiency generally increases the tolerance and/or resistance of plants to diseases.
6. Copper, B, and Mn influence the synthesis of lignin and simple phenols. Silicon appears to affect physical barriers to invasion.
7. The greatest benefits from nutrients are found with moderately susceptible or partially resistant cultivars. In highly resistant and highly susceptible cultivars, the nutritional status of the plant has little influence on the severity of disease.
8. Nutritional balance is as important as the level of a single nutrient in disease control.
9. No nutrient controls all diseases or favors disease control on all groups of plants. Therefore, all control practices should be integrated for optimum plant growth and production.
10. Some nutrients appear to affect disease severity simply through greater tolerance, for example, P and S. Others, including N and K, alter specific host-plant resistance mechanisms.

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8 Wheat and Barley

8.1 INTRODUCTION

Wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) together constitute the world's most important cereal crops. Wheat is the third cereal in terms of total world production after corn and rice, and barley is the world's fourth most important cereal crop after wheat. These two cereals contribute about 41% of the world production of important cereal crops. Winter wheat and barley cultivars are planted in the autumn or winter and usually require vernalization for normal phenological development. Spring cultivars are planted in the spring in temperate climates or in the winter or autumn in lower latitudes where temperatures are too high for vernalization of winter cultivars.

Wheat and barley are crops of great antiquity and were first cultivated in western Asia at least 9000 years ago. All the important early civilizations were based on some kind of cereal—wheat and barley in the Middle East and Mediterranean, rice in southern and eastern Asia, and corn in the New World (Purseglove, 1985). During the end of the twentieth century, developing countries have raised wheat production more rapidly than have wheat-producing countries of the developed world. The increase in production was mainly due to use of better-adapted high-yielding, semidwarf cultivars, and better management practices. Cox et al. (1988) reported that breeding efforts alone had increased grain yields of hard red winter wheat in the Great Plains of the United States by about 1% of the baseline yield per year between 1919 and 1987. In reviewing the literature, Austin et al. (1989) concluded that genetic improvement in winter wheat yields in several countries around the world increased by 0.4%–0.8% year^{-1}. Yield potential of malting barley has increased during the twentieth century due to the effect of plant breeding (Abeledo et al., 2003, 2008) at a rate similar to increases for other cereals (Abeledo et al., 2003). Abeledo et al. (2003) reported that barley yield increased during the second half of the twentieth century, with a relative genetic gain of 0.5% year^{-1}. In wheat, genetic improvement raised grain yields under both high- and low-input environments (Reynolds and Borlaug, 2006).

Under favorable environmental conditions, modern wheat cultivars are capable of efficiently converting solar radiation into plant biomass. Singer et al. (2007) reported that during the linear phase of cereal growth, radiation use efficiency (RUE) averaged across plant density varied from 3.37 to 3.50 g MJ^{-1} depending on the year of cultivation. However, in the long term, there is a need for continued improvements in yield and quality of all major crops, including wheat and barley, through genomics and gene pyramiding (Swaminathan, 2007). For example, super wheats capable of yielding about 8 Mg ha^{-1} are now in the breeders assembly line (Ginkel and Ogbonnaya, 2007). These super wheats are semidwarfs with robust stems, broad leaves, large spikes with a greater number of grain per head, and higher grain weights (Swaminathan, 2007).

The leading wheat- and barley-producing countries in the world are China, India, the United States, Canada, USSR, Australia, France, the United Kingdom, Germany, Argentina, Turkey, and Pakistan. Detailed data related to production in different continents, yield per hectare, and area planted are given by Briggle and Curtis (1987) for wheat and by Poehlman (1985) for barley.

Both of these cereals are important sources of food for human consumption and feed for livestock. On a worldwide scale, wheat contributes approximately 30% of total cereal production (FAO, 1992), making wheat a major source of nutrition for many people. The most important food product made from wheat is flour, which is used to make breads, pastas, and cakes. Wheat starch is used for laundering, paper laminating and corrugating, adhesives, textiles, wallpaper, billboard paste, and paper additives (Miller, 1974). Low-grade wheat also is fermented for the production of

alcohol. Similarly, the use of barley malt in brewing is well known. Several of the cereal grains may be used for malt, but barley, wheat, and rye are unique in the production of α-amylase and β-amylase enzymes, which hydrolyze starch to dextrans and fermentable sugars (Peterson and Foster, 1973; Dickson, 1979).

Grain protein content is one of the most important malt quality traits in barley. Protein content of barley grain malted in the United States should not exceed 135 g kg^{-1} for Midwestern six-rowed genotypes and 130 g kg^{-1} for Western two-rowed genotypes. Grain protein content that exceeds recommended levels is undesirable for malting because it may increase steep times and may cause uneven water uptake during steeping, uneven germination during malting, increasing malt loss due to abnormal growth, excessive enzymatic activity, low extract yields, excessive nitrogenous compounds in the wort during brewing, and chill haze formation in beer (Goblirsch et al., 1996).

8.2 CLIMATE AND SOIL REQUIREMENTS

Wheat and barley are the most important cereals of the temperate regions, but they are also grown at high altitudes in the tropics and even extend into the tropical lowlands. Wheat production is concentrated between latitudes 30°N and 60°N and 27°S and 40°S (Nuttonson, 1955), but it is also a major crop in India. Similarly, barley has a broad ecological adaptation. It is grown at latitude 64°N in Alaska, latitude 67°N in Finland, and latitude 70°N in Norway. It is the only cereal that matures at these high latitudes (Nuttonson, 1955). Hard red winter wheat is a cool-season crop that is most productive when planted in autumn since cool weather from emergence to the early reproductive stage favors tillering and the subsequent development of large spikes (Otteson et al., 2008). The minimum temperature for growth of wheat is about 3°C–4°C, the optimum temperature is about 25°C, and the maximum is about 30°C–32°C (Briggle, 1980). Barley has similar temperature requirements for growth.

Environment strongly affects yield of wheat and barley (Rassmuson and Cannell, 1970; Garcia et al., 2003; Anderson, 2008; Chen et al., 2008). Among environmental factors, availability of water and temperature are important. Yield components like number of spikes per unit area, number of grain per spike, and mean grain weight are reduced by water and temperature stresses. Wheat and barley can withstand heat in a dry climate or high humidity in a cool climate, but they perform poorly in a hot, humid climate due to increased infestation of diseases. Wheeler et al. (1996) reported that temperatures higher than 31°C during grain filling can cause sterile grains. In addition, high temperatures and humidity prior to and during the early stages of grain development affect grain setting, producing shrivelled grains (Tashiro and Wardlaw, 1990). Both these cereals may be injured by frost during the flowering and early grain-filling periods.

Short periods (3–5 days) of very high temperature (33°C–40°C) can markedly reduce the yield and quality of wheat (Randall and Moss, 1990). The tolerance of wheat yield to very high temperatures is known to vary with genotypes. Genotypic variation in response to high temperature of about 20% was recorded for the majority of yield and quality components by Stone and Nicolas (1995). The fact that responses of this magnitude were caused by exposure to high temperatures lasting only 5%–6% of the grain-filling period demonstrates the extent to which short periods of very high temperature may affect wheat yield and quality (Stone and Nicolas, 1995). Fischer (1985) showed that the critical period for grain number determination spans about 20 days before anthesis. Further studies extended the critical period from 20 days before to 10 days after anthesis (Abbate et al., 1995, 1997). High temperatures during the critical period may reduce grain number as well as grain weight and, consequently, grain yield of wheat and barley. Genetic variability in yield and yield components among wheat and barley genotypes has been reported (Li et al., 2000).

The availability of water is a major factor limiting cereal production in most regions of the world. Wheat can be grown in regions where annual precipitation ranges from 250 to 1750 mm; about three fourths of the land area used for wheat production receives an average of 375–875 mm annually (Briggle and Curtis, 1987). Drought stress may cause a reduction in all the yield components and,

consequently, reduce grain yield (Giunta et al., 1993; Abayomi and Wright, 1999; Moragues et al., 2005). For example, the response of wheat to six levels of soil-water tension was studied under field conditions in an Oxisol of the Brazilian Savannah Region (Guerra, 1995). The crop was irrigated when the soil-water tension, measured with tensiometers or gypsum blocks, reached values of 41, 51, 69, 185, 562, and 993 kPa at a depth of 10 cm throughout the crop cycle. Grain yields decreased with the increase in soil-water tension. The highest yield (6952 kg ha^{-1}) was obtained with the lowest soil-water tension (41 kPa). The yield components that caused reduction in yield were the number of spikes per square meter, the number of spikelets per spike, and the number of grains per spike. No significant difference was observed for the 1000-grain weight and the hectoliter-grain weight.

Wheat is widely grown under rainfed conditions in many countries, and water limitation frequently reduced grain yield (Loss and Siddique, 1994; Bennet et al., 1998; Dreccer et al., 2007; Mazzoncini et al., 2008). The annual yield loss to drought, which typically occurs post-anthesis in the United Kingdom, is about 15% (Austin, 1978; Foulkes et al., 2002). With predicted climate change and more frequent summer droughts these losses will be exacerbated. Genetic improvement may be one way of combating these drought effects (Foulkes et al., 2007). The production of synthetic bread wheats (SBWs), through interspecific hybridization of the original donors of the wheat genome, is one of the strategies employed at (International Maize and Wheat Improvement Center) CIMMYT to address this issue (Trethowan, 2004). Briefly, SBWs are obtained by crossing modern durum wheats (*Triticum turgidum* L.), donor of the AB genome, with wild progenitor goat grass (*Aegilops tauschlii* L.), donor of the D genome, and backcrossing this amphiploid to locally adapted wheat cultivars (Dreccer et al., 2007). This approach has been mainly aimed at broadening the restricted variation in the D genome present in modern wheats, since only a few accessions of *Aegilops tauschii* L. were likely involved in the hybridizations that led to the original bread wheats 8,000–10,000 years ago (Apples and Lagudah, 1990). In addition, this methodology capitalizes on the fact that *Aegilops tauschii* L. evolved and thrives in marginal, water-scarce environments (Dreccer et al., 2007). There is widespread evidence for genotypic variation in the root characteristics of wheat and its impact on drought resistance (Ludlow and Muchow, 1990; Hoad et al., 2001; Manchadi et al., 2008). Hence, planting drought-resistant cultivars is an important strategy to improve wheat yields in water-deficit environments.

Barley is often regarded as a drought-resistant crop. The water requirement for production of a unit weight of grain is less than for other cereals (Carlton, 1916), its transpiration rate being the lowest among the small grains (Nuttonson, 1955). Almost two thirds of the world's barley production is in subhumid or semiarid regions (Poehlman, 1985). Barley is an important crop in arid and semiarid regions of the United States. According to the U.S. Department of Commerce, slightly over 20% of barley is irrigated (Anonymous, 1979). The report indicated that the average yield of irrigated barley was about 4000 kg ha^{-1}, compared to about 2000 kg ha^{-1} for nonirrigated barley.

In tropical climates with less than 200 mm precipitation during the growing season, irrigation is necessary to produce good yields of wheat and barley. Rainfall distribution during crop growth is a critical factor in most production environments. To minimize water stress, irrigation should be scheduled so that the available soil water in a 120 cm profile does not fall below 50%–60% (Baldridge et al., 1985). Interpretation of plant responses to drought is complicated by the fact that soil strength and water stress are highly correlated (Whalley et al., 2007). Small decreases in soil matric potential (to −80 kPa) can produce large increases in soil strength and decreases in wheat yields (Whalley et al., 2006; Whalley et al., 2008). This raises the possibility that high soil strength as well as low matric potential can limit wheat growth. Wheat and barley can be grown on a variety of soils, but reasonable drainage and good water-holding capacity are preferred. Both these cereals are considered medium acid-tolerant (Adams, 1981; Carver and Ownby, 1995); but according to Doll (1964), the permissible soil pH range for wheat is 5.5–7, whereas for barley the range is 6.5–7.8. Bower and Fireman (1957) also reported that barley is more tolerant than other cereal crops to alkaline soils and less tolerant to acid soils. Poehlman (1985) found that soil pH in the range of 6–8.5 is generally acceptable for barley growth (Poehlman, 1985). Farhoodi and Coventry (2008) also reported that in Australia, maximum

yields of wheat and barley were obtained at pH_{ca} 6.0. Similar results were also reported for wheat and barley by Liu et al. (2004) in southeastern Australia. These authors also reported that barley was more susceptible to soil acidity compared to wheat.

Figure 8.1 shows root dry weight of wheat as a function of increasing soil pH in an Oxisol of central Brazil. Root dry weight increased with increasing soil pH up to a value of about 6,

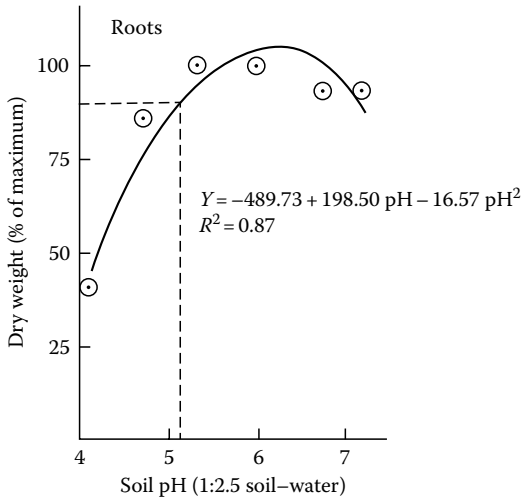

FIGURE 8.1 Relationship between soil pH and dry weight of roots of wheat in an Oxisol.

TABLE 8.1
Grain Yield (kg ha^{-1}) of Wheat Genotypes under Different Aluminum Saturation

	Aluminum Saturation (%)[a]				
Genotype	**0**	**15**	**30**	**45**	**Mean**
Trigo BR 23	2928a	2773B	2511B	2262C	2619B
IAPAR 29	3411a	2884B	2311B	1431D	2510B
IAPAR 60	3505a	3219A	2886A	2564B	3043A
OCEPAR 16	3391a	2518B	2254B	2233C	2599B
Trigo BR 35	3505A	3367A	3225A	3023A	3280A
IAPAR 6	3286A	2836B	2813B	2297C	2808B
IAPAR 53	3384A	3252A	2918A	2503B	3014A
Trigo BR 18	3420A	2843B	2454B	2291C	2752B
IAC 5-Maringà	3444A	3179A	3116A	2845A	3146A
Anahuac	3308A	2161B	1521C	1189D	2045C
Mean	3358a	2903b	2601c	2264d	2782
F[b]	0.44	3.72**	4.64**	9.40**	12.68**
CV (%)	12.97	11.47	15.56	14.19	14.04

Source: Costa, A. et al., Reaction of wheat genotypes to soil aluminum saturation, in *Paper Presented at the 4th International Symposium on Soil–Plant Interactions at Low pH*, Belo Horizonte, Brazil, March 17–24, 1996.

[a] Means followed by the same capital letters in the columns, and lower case letters in the rows, do not differ significantly among themselves by the Scott–Knott test at 5% probability.

[b] Significant to a 1% (**) probability level.

then it decreased, suggesting that in Oxisols pH should be raised to 6 for optimum wheat growth. Aluminum is an important component of soil acidity, and genotype differences in Al tolerance have been reported for wheat (Table 8.1).

Both wheat and barley are also considered to be medium tolerant to soil salinity. Salinity at initial yield decline (threshold) is reported to be about 6 dS m^{-1} for both species (Maas and Hoffman, 1977). However, differences in tolerance to salinity exist among cultivars in both species.

8.3 GROWTH AND DEVELOPMENT

As discussed above, plant growth and development are influenced by both environmental and genetic factors (Evans, 1987; Fageria, 1992; Slafer and Rawson, 1994; Arisnabarreta and Miralles, 2008). A good understanding of growth and development can help producers implement appropriate management practices and obtain higher yields. Attention to plant phenology can help guide the timing of N topdressing to stimulate growth and reduce fertilizer N losses. In addition, irrigation can be scheduled at critical growth stages to improve water-use efficiency. Further, an understanding of the crop growth cycle in a given agroecological region can help the producer schedule planting to avoid drought and possible adverse effects of low and high temperatures. Knowledge of growth stages is also useful in scheduling tissue sampling at different locations. In addition to visual morphological observations (Haun, 1973; Zadoks et al., 1974; Hay and Kirby, 1991; Kirby et al., 1994; Jamieson et al., 1995; Jamieson and Munro, 1999), models of phenological development of cereals, including wheat and barley, have been developed (Laurie et al., 2004; Jamieson et al., 2006; Sinclair and Jamieson, 2006).

Plant growth and development are complex processes, depending on many factors both internal and external. They can be considered to begin with germination, followed by a large complex series of morphological and physiological events that are called growth and development (Ting, 1982; Fageria, 1992; Fageria et al., 2006). These two terms are sometimes confused and used interchangeably, but they are different. Growth is an irreversible increase in size or volume accompanied by the biosynthesis of new protoplasmic constituents. Development is a combination of both growth and cellular differentiation, a higher order of change that involves anatomical and physiological specialization and organization. According to Salisbury and Ross (1985), the process by which cells become specialized is called differentiation, and the processes of growth and differentiation of individual cells into tissues and organs are often called development. Another useful term for this process is morphogenesis.

According to the above definition, growth is a quantitative aspect of development, representing an increase in the number and size of cells, and differentiation is the qualitative aspect of development (Ting, 1982; Fageria et al., 2006). Growth is usually measured in terms of increase in volume or weight of the crop plant or its organ. In field crops, productivity is the main objective of cultivation; in this situation, dry weight of the plant or plant parts is the preferred measurement of growth. Figure 8.2 shows the growth curve of root and shoot dry weight of the wheat plant as a function of time. Root and shoot growth was slow in the beginning, increased until 60 days, then remained more or less constant. But shoot growth increased significantly after about 35 days and continued to increase until maturity. The slow early growth of the shoot may be attributed to the relatively small number of cells that can divide, the small leaf area available for light interception and photosynthesis, and the relatively large percentage of photosynthate translocated to the roots (Brown, 1984; Fageria et al., 2006). The root system is a very important organ of the plant which provides mechanical support and absorbs nutrients and water. The root systems of wheat and barley consist of three to six primary or seminal roots growing from the seed and the secondary roots (also called nodal, crown, or adventitious roots) that arise from nodes at the base of the main stem and tillers. Each tiller develops its own roots and can thus become independent of other shoots (Hoad et al., 2001). According to Figure 8.2, the roots contribute about 15% of the total weight of the wheat plant at 60 days of growth and

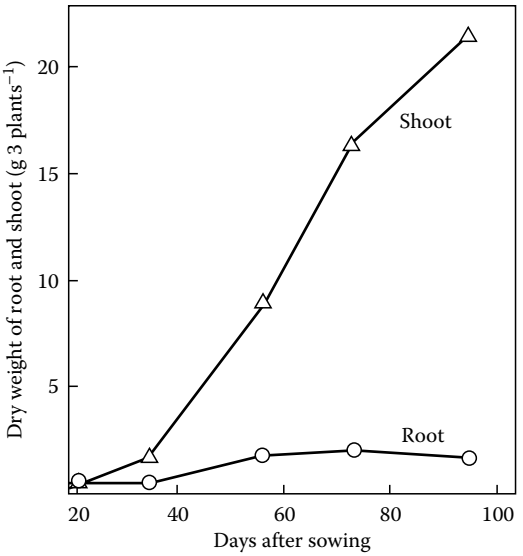

FIGURE 8.2 Dry weight of root and shoot of wheat plant days after sowing in Oxisol of central Brazil under greenhouse conditions. (From Fageria, N.K., *Pesq. Agropec. Bras*., 25, 530, 1990.)

3% at maturity. The extent of the root system is more important than its weight because a small weight of roots can absorb large amounts of water and mobile nutrients like nitrate when soil conditions are favorable.

In wheat the culm usually has six nodes, although culms with five or seven are not uncommon (Peterson, 1956; Briggle, 1967). Genetypic differences in tiller formation exist among cultivars due to inherent genetic factors (Hucl and Baker, 1989). As a result, cultivars vary significantly in the number of tillers produced, with many producing only one or two tillers (Otteson et al., 2008). Donald (1968) proposed that a uniculm plant of wheat could be more appropriate than freely tillering cultivars for well-watered crops with high nutrient inputs. Visual quantification of wheat development is provided by Haun (1973). Bauer et al. (1987) studied dry matter distribution in wheat and showed that the leaves constitute 100% of shoot dry matter after emergence, about 50% at the flag-leaf stage, and 20% at anthesis. According to Waldren and Flowerday (1979), dry matter accumulation in winter wheat increases rapidly from the jointing growth stage through grain in the stiff dough stage. Translocation of dry matter from leaves to grain begins at flowering, and translocation from culms and head to grain begin at grain filling. Plant growth occurs through cell division and cell elongation. Areas where cells are actively dividing are called meristem regions. The plant embryo contains only meristem tissue, so all plant parts such as roots, stems, leaves, and flowers are derived from the meristem (Stoskopf, 1981). Kemanian et al. (2007a) reported that the supply of dry matter depends on current photosynthesis and pre-stored reserves. A detailed description of growth and development of barley is given by Wych et al. (1985) and of wheat by Simmons (1987).

8.3.1 Growth Analysis

Growth analysis is the procedure of analyzing plant growth rate by expressing it as the algebraic product of a series of factors (Hardwick, 1984). The growth analysis formulas, together with necessary and sufficient conditions for their use, have been discussed in several articles (Emecz, 1962; Radford, 1967; Evans, 1972; Hunt, 1979; Charles-Edwards and Fischer, 1980; Warren, 1981; Wilson, 1981; Jolliffe et al., 1982; Brown, 1984; Hardwick, 1984; Fageria, 1992). Growth is analyzed principally as crop growth rate (CGR), relative growth rate (RGR), and net assimilation rate (NAR).

The plant parameters that are commonly measured to calculate growth rates are plant height, dry matter, tillering in cereals, and leaf area (Fageria, 1992).

8.3.1.1 Crop Growth Rate

The dry matter accumulation rate per unit of land area is referred to as CGR, normally expressed as g m^{-2} day^{-1} (Brown, 1984). It can be calculated with the help of the following formula:

$$\mathrm{CGR} = \frac{W_2 - W_1}{\mathrm{SA}(t_2 - t_1)}$$

where

W_1 and W_2 are crop dry weight at the beginning and end of the interval
t_1 and t_2 are corresponding days
SA is the soil area occupied by the plants at each sampling

Crop growth pattern can be defined accurately by taking plant samples at different time intervals during the growing season. CGR is normally low in the early growth stage and increases with time, reaching a maximum value around flowering. CGR studies help in the interpretation of experimental results of different crop cultivars and other management practices and in the evaluation of fertility status of the soils. Prerequisite to the calculation of growth rate is the designation of uniformly spaced stages of development that can be recognized by the observer. There must be a continuity of time interval among stages and among the intermediate divisions of stages to provide for subsequent numerical analyses or correlation with independent variables (Haun, 1973).

8.3.1.2 Relative Growth Rate

The RGR of a plant at an instant in time (t) is defined as the increase of plant material per unit of material present per unit of time (Radford, 1967). It can be calculated with the help of the following formula and expressed in g (g dry weight)$^{-1}$ day^{-1}:

$$\mathrm{RGR} = \frac{1}{W} = \frac{\mathrm{d}W}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}(\log_e W)$$

where

W is the dry weight
dW/dt is the change in dry weight per unit time

8.3.1.3 Net Assimilation Rate

The dry matter accumulation per unit of leaf area is termed NAR and is expressed as g (m leaf area)$^{-2}$ day^{-1} (Brown, 1984). It can be computed with the help of the following formula:

$$\mathrm{NAR} = \frac{1}{A}\,\frac{\mathrm{d}w}{\mathrm{d}t}$$

where

A is the leaf area
dw/dt is the change in plant dry matter per unit time

The objective of measuring NAR is to determine the efficiency of plant leaves in dry matter production. NAR decreases with crop growth due to mutual shading of leaves and reduced photosynthetic efficiency of older leaves.

8.3.2 Growth Stages

From germination until harvest, the crop plant develops through different growth stages that are determined by environmental factors, cultivar characteristics, and cultural practices. Knowledge of these growth stages is useful in deciding the right time for cultural operations such as topdressing of N and application of herbicides, insecticides, and fungicides. Further, growth stage is a key factor determining the critical stages in the life cycle that are sensitive to environmental factors affecting crop yield and its components. For example, in cereals the reproductive and ripening stages are more sensitive to water deficiency than the vegetative stage (Yoshida, 1972). In wheat the embryo ear has its full complement of spikelets well before the ear emerges from the flag-leaf sheath, and any treatment intended to increase spikelet number per ear must consider this (Kirby and Appleyard, 1984).

The most common method for identifying growth stages in cereals is known as the Feekes scale (Table 8.2). The Feekes scale is based on the external appearance of the plant or plant organs. The Feekes scale was improved by Zadoks et al. (1974) and later reproduced by Tottman and Makepeace (1979) and Tottman (1987) with drawings of selected growth stages of wheat, barley, and oats. The whole growth cycle of cereals is divided into 10 principal growth stages, and each principal growth stage is subdivided into secondary growth stages. A detailed description of these principal and secondary growth stages is given in Table 8.3. Some of the growth stages representing wheat and barley growth and development from germination to ripening are present in Figures 8.3 through 8.10.

TABLE 8.2
Growth Stages in Cereals Based on the Feekes Scale

Growth Stage	Description	
1	One shoot (number of leaves can be added) = "braiding."	Tillering
2	Beginning of tillering.	
3	Tillers formed, leaves often twisted spirally. In some varieties of winter wheat, plants may be "creeping" or prostate.	
4	Beginning of the erection of the pseudostem, leaf sheaths beginning to lengthen.	
5	Pseudostem (formed by sheaths of leaves) strongly erected.	
6	First node of stem visible at base of shoot.	Stem extension
7	Second node of stem formed, next to last leaf just visible.	
8	Last leaf visible, but still rolled up, ear beginning to swell.	
9	Ligule of last leaf just visible.	
10	Sheath of last leaf completely grown out, ear swollen but not yet visible.	
	10.1 First ears just visible (awns showing in barley, ear escaping through split of sheath in wheat or oats).	Heading
	10.2 Quarter of heading process completed.	
	10.3 Half of heading process completed.	
	10.4 Three quarters of heading process completed.	
	10.5 All ears out of sheath.	
	10.5.1 Beginning of flowering (wheat).	Flowering
	10.5.2 Flowering complete to top of ear.	
	10.5.3 Flowering over at base of ear.	
	10.5.4 Flowering over, kernel watery ripe.	
11.1	Milky ripe.	Ripening
11.2	Mealy ripe, contents of kernel soft but dry.	
11.3	Kernel hard (difficult to divide by thumbnail).	
11.4	Ripe for cutting. Straw dead.	

Source: Large, E.C., *Plant Pathol.*, 3, 128, 1954. With permission.

TABLE 8.3
Cereal Growth Stages: Description of the Principal and Secondary Growth Stages

0 Germination
- 00 Dry seed
- 01 Start of imbibition (water absorption)
- 02 —
- 03 Imbibition complete
- 04 —
- 05 Radicle (root) emerged from caryopsis (seed)
- 06 —
- 07 Coleoptile (shoot) emerged from caryopsis
- 08 —
- 09 Leaf just at coleoptile tip

1 Seedling growth
- 10 First leaf through coleoptile
- 11 First leaf unfolded
- 12 Two leaves unfolded
- 13 Three leaves unfolded
- 14 Four leaves unfolded
- 15 Five leaves unfolded
- 16 Six leaves unfolded
- 17 Seven leaves unfolded
- 18 Eight leaves unfolded
- 19 Nine or more leaves unfolded

2 Tillering
- 20 Main shoot only
- 21 Main shoot and one tiller
- 22 Main shoot and two tillers
- 23 Main shoot and three tillers
- 24 Main shoot and four tillers
- 25 Main shoot and five tillers
- 26 Main shoot and six tillers
- 27 Main shoot and seven tillers
- 28 Main shoot and eight tillers
- 29 Main shoot and nine or more tillers

3 Stem elongation
- 30 Ear at 1 cm (pseudostem erect)
- 31 First node detectable
- 32 Second node detectable
- 33 Third node detectable
- 34 Fourth node detectable
- 35 Fifth node detectable
- 36 Sixth node detectable
- 37 Flag leaf just visible
- 38 —
- 39 Flag leaf ligule just visible

4 Booting
- 40 —
- 41 Flag leaf sheath extending

(*continued*)

TABLE 8.3 (continued)
Cereal Growth Stages: Description of the Principal and Secondary Growth Stages

42 —
43 Boots just visibly swollen
44 —
45 Boots swollen
46 —
47 Flag sheath opening
48 —
49 First awns visible

5 Inflorescence (ear/panicle emergence)
50 —
51 First spikelet of inflorescence just visible
52 —
53 1/4 of inflorescence emerged
54 —
55 1/2 of inflorescence emerged
56 —
57 3/4 of inflorescence emerged
58 —
59 Emergence of inflorescence Completed

6 Anthesis (flowering)
60 —
61 Beginning of anthesis
62 —
63 —
64 —
65 Anthesis halfway
66 —
67 —
68 —
69 Anthesis complete

7 Milk development
70 —
71 Caryopsis (kernel) water ripe
72 —
73 Early milk
74 —
75 Medium milk
76 —
77 Late milk
78 —
79 —

8 Dough development
80 —
81 —
82 —
83 Early dough
84 —

TABLE 8.3 (continued)
Cereal Growth Stages: Description of the Principal and Secondary Growth Stages

85 Soft dough
86 —

9 Ripening
90 —
91 Caryopsis hard (difficult to divide)
92 Caryopsis hard (difficult to divide)
93 Caryopsis loosening in daytime
94 Overripe, straw dead and collapsing
95 Seed dormant
96 Viable seed giving 50% germination
97 Seed not dormant
98 Secondary dormancy induced
99 Secondary dormancy lost

Source: Tottman, D.R., *Ann. Appl. Biol.*, 110, 441, 1987. With permission.

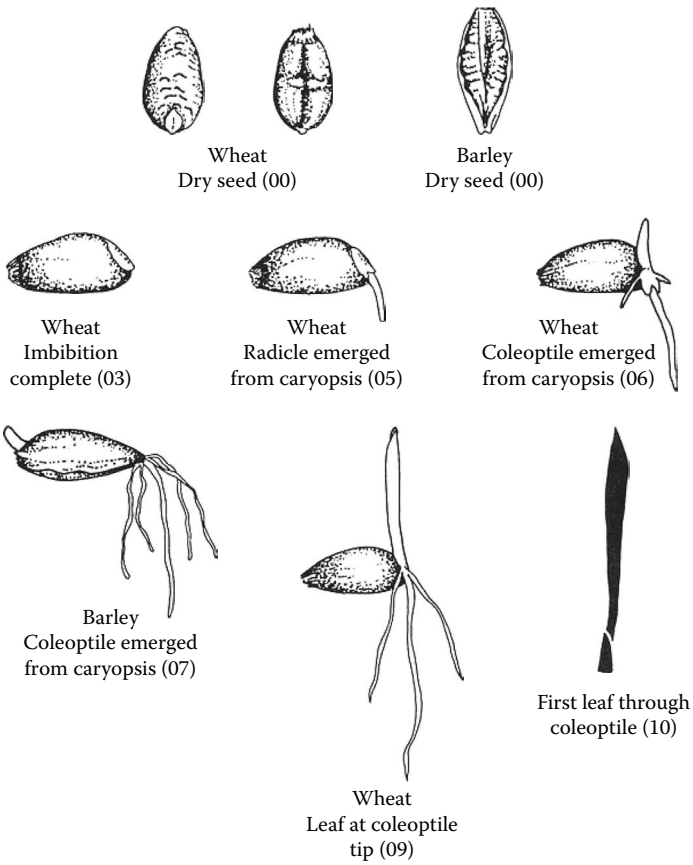

FIGURE 8.3 Germination and seedling growth in wheat and barley. (From Tottman, D.R., *Ann. Appl. Biol.*, 110, 441, 1987. With permission.)

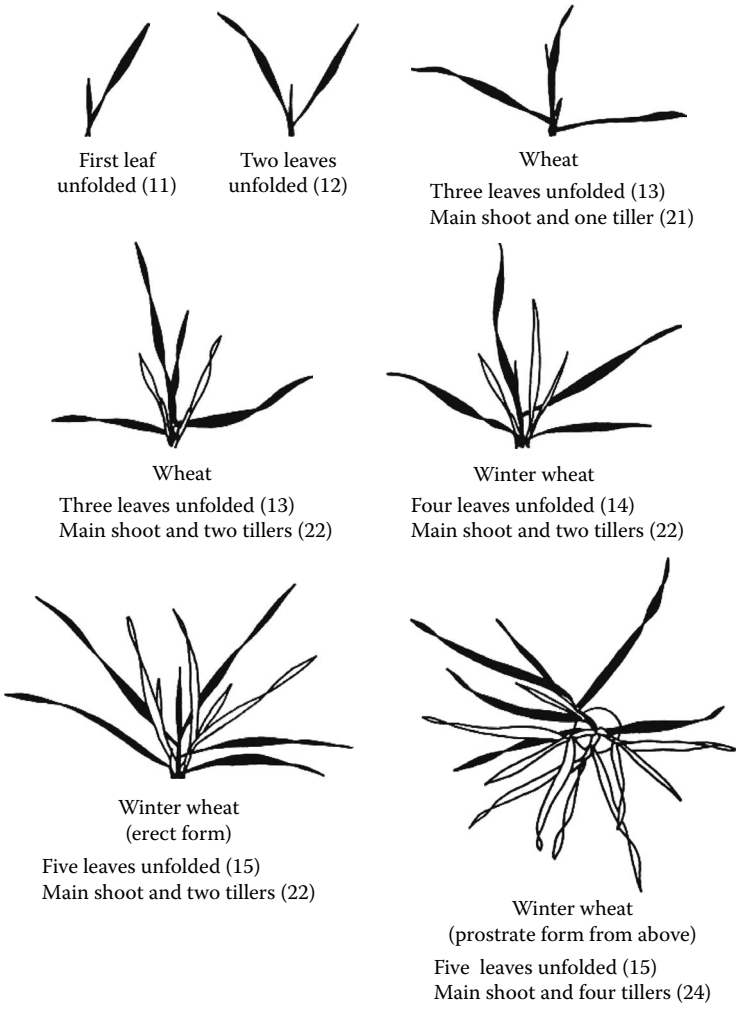

FIGURE 8.4 Seedling growth and tillering in wheat. (From Tottman, D.R., *Ann. Appl. Biol.*, 110, 441, 1987. With permission.)

During the seedling growth stage, only leaves on the main shoot should be counted, excluding tillers and their leaves. A leaf can be described as unfolded when its ligule has emerged from the sheath of the preceding leaf (Tottman, 1987). The inflorescence development of cereals has been described in detail by Bonnet (1966), Nerson et al. (1980), Kirby and Appleyard (1984), Reid (1985), and Lersten (1987), and readers may refer to these publications for detailed information.

Waldren and Flowerday (1979) also gave a growth description for winter wheat based on a 10-point scale (Table 8.4). According to these authors, the growth stages described by the Feekes scale are not easily distinguished by farmers because the scale is based on small morphological changes that are not readily apparent, especially at the later stages. Waldren and Flowerday (1979) claim that the growth stages they described (Table 8.4) are identified by morphological changes that are easily detected by farmers, students, and others.

8.3.3 Partitioning of Dry Matter

Partitioning of photosynthetic products into vegetative and reproductive organs is key to crop growth and development. Wheat and barley are determinate plants that allocate photosynthetic products to

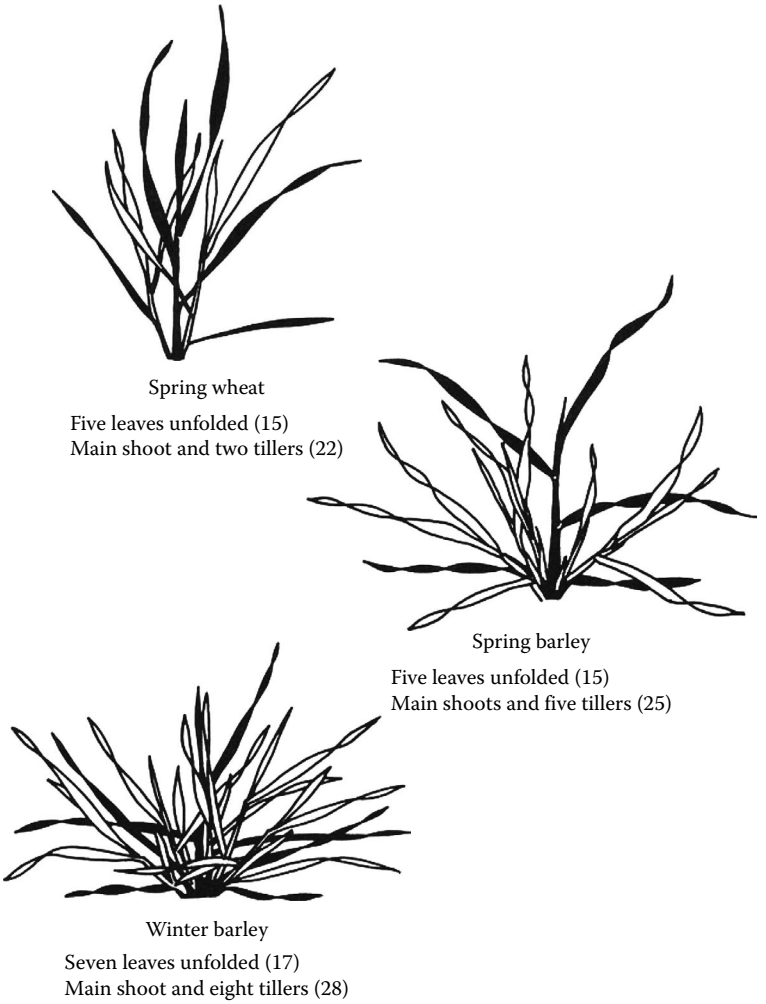

FIGURE 8.5 Seedling growth and tillering in wheat and barley. (From Tottman, D.R., *Ann. Appl. Biol.*, 110, 441, 1987. With permission.)

vegetative growth early in the season and to grain later (Brown, 1984). Over the last half century, grain yield improvement in cereals like wheat and barley has been achieved through an increase in harvest index and a decrease in plant height (Polisetty et al., 1993). Grain harvest index, the ratio of grain to total biological yield, is a measure of the degree to which a crop partitions photosynthetic products into grains (Donald and Hamblin, 1976; Wych et al., 1985; Fageria and Baligar, 2005; Fageria, 2009). Grain harvest index in wheat has increased substantially through breeding (Austin et al., 1980; Bulman et al., 1993; Muurinen et al., 2006), and these improvements have largely contributed to improve nitrogen use efficiency (Muurinen et al., 2006). In wheat, the grain harvest index reported in the literature is around 0.34 in traditional old cultivars and about 0.44 in improved new cultivars (CIMMYT, 1972; Ehdaie and Waines, 2001; Lopez-Bellido et al., 2006). This means that the recent gains in wheat yield with modern cultivars can be attributed to improved grain harvest index. Similarly, in Britain, the grain harvest index for barley increased from 0.33 to 0.50 between 1880 and 1980 (Riggs et al., 1981), and in the United States the harvest index of midwestern malting barley increased from 0.27 to 0.40 between 1920 and 1978 (Wych and Rasmusson, 1983). Kemanian et al. (2007b) reported that grain harvest index of barley in Uruguay varied from 0.44 to 0.53. In Italian and Spanish durum wheat, the yield increases in modern cultivars are mostly associated with increasing harvest index, shorter periods from

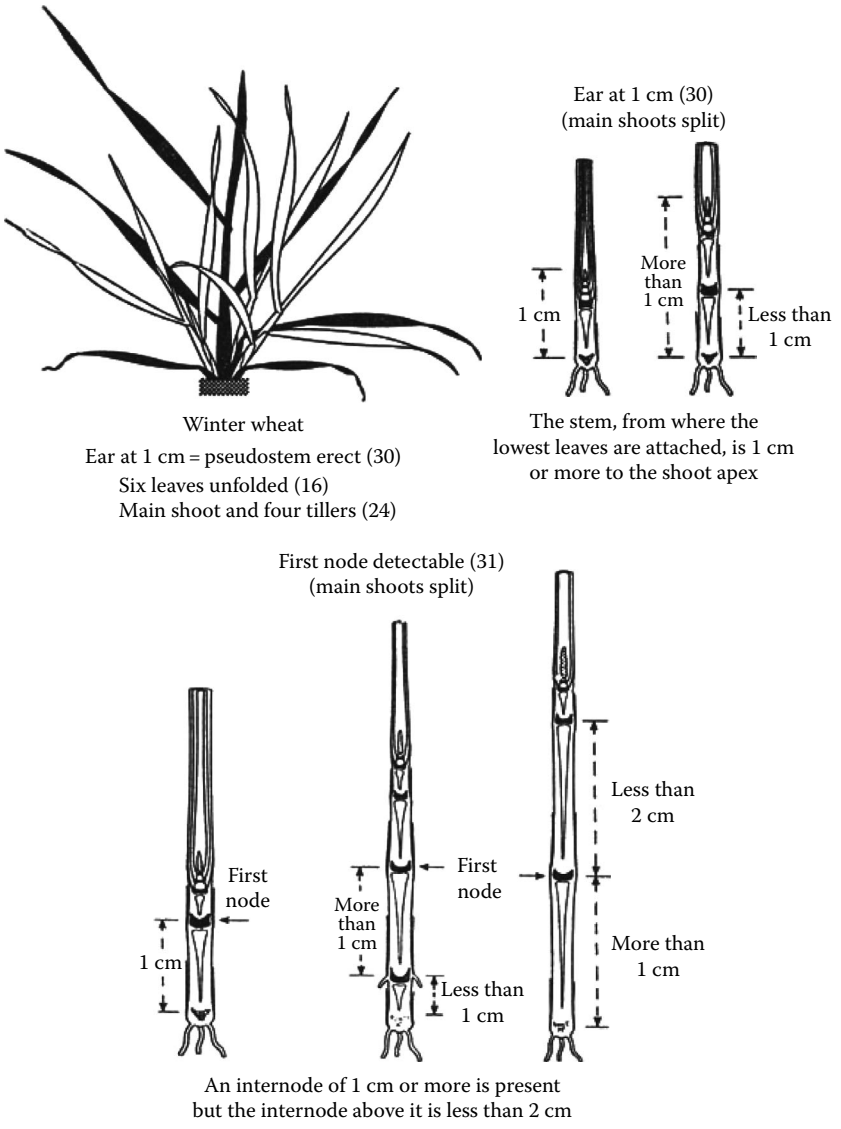

FIGURE 8.6 Stem elongation in winter wheat. (From Tottman, D.R., *Ann. Appl. Biol.*, 110, 441, 1987. With permission.)

sowing to anthesis, and more grains per unit area (De Vita et al., 2007; Royo et al., 2007; Alvaro et al., 2008). Grain weight have remained unchanged (De Vita et al., 2007; Royo et al., 2007) or have slightly decreased (Pfeiffer et al., 2000). Austin et al. (1980) suggest that harvest index of cereals might be increased from the current range of 0.4–0.5 to around 0.6 before diminishing return sets in. This suggests that there is considerable scope for improving wheat and barley yield by improving harvest index.

8.3.4 Relationship between Growth and Yield

In a broad sense, growth in cereals is directly related to grain yield. Grain yield is the product of the number of grains per unit area and the weight of individual grains (Peltonen-Sainio et al., 2007). The number of grains per unit area is determined by the number of ears per unit area and the number of grains per ear (Gales, 1983; Gambin et al., 2006). After the ear is formed and the maximum number of grains per ear has been determined, grain weight depends on translocation of carbohydrates

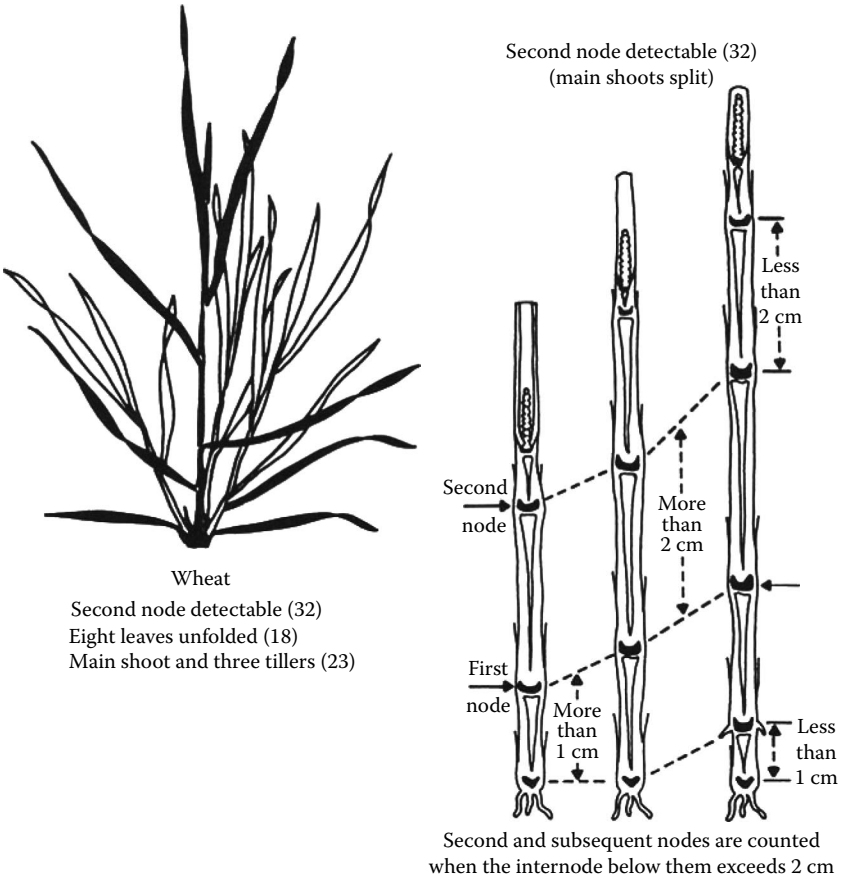

FIGURE 8.7 Stem elongation in winter wheat. (From Tottman, D.R., *Ann. Appl. Biol.*, 110, 441, 1987. With permission.)

to the grains, principally from the leaves and ears (Carrasco and Thorne, 1979). Yield of grain is highly dependent on the photosynthetic capacity of the crop after anthesis and the ability of the grains to store carbohydrates translocated to them (the sink capacity of the grain) (Bingham et al., 2007a,b). The control of grain filling has often been considered in terms of the supply of photosynthate (source limitation) or the capacity of the grain to accumulate available carbohydrate (sink limitation) (Bingham et al., 2007a). Carbohydrates for grain filling are supplied concurrently from photosynthetic activity and from temporary storage reserves (Schnyder, 1993). Sink capacity is a function of the number of grains per unit area and their potential size. It is not clear what the mechanisms determining potential grain size are, but both genetic and environmental factors are involved (Bingham et al., 2007a). Genotypic differences in mean grain weight in wheat and barley have been related to variation in endosperm cell number established during early grain development and the number of starch granules (Cochrane and Duffus, 1983). However, earlier development events may also be important in contributing to potential grain size through effects on carpel weight at anthesis (Calderini et al., 1999; Bingham et al., 2007a).

The importance of pre- as well as post-anthesis environmental conditions in determining the grain weight of cereals has been highlighted for crops grown in warm low latitudes (Calderini et al., 1999, 2001, 2006). Similarly, Bingham et al. (2007a,b) demonstrated that both pre- and early post-anthesis conditions are important determinants of potential grain weight in barley grown in the cool long day climate of the United Kingdom. These authors further reported that the most influential factors were the mean air temperature during booting and ear emergence and the amount of radiation intercepted per unit grain number during the period of early grain development.

FIGURE 8.8 Booting growth stage in wheat and barley. (From Tottman, D.R., *Ann. Appl. Biol.*, 110, 441, 1987. With permission.)

Under optimum conditions, the contribution of pre-anthesis photosynthate reserves to final grain weight was found to be 5%–10% in wheat and 20% in barley (Sharma, 1992). The photosynthetic capacity after anthesis is mainly dependent on leaf area duration, which is a function of leaf area index (LAI) at anthesis and leaf longevity (Bingham, 1969). McCaig and DePauw (1995) analyzed wheat trials data from western Canada from 1947 to 1992. Historical data from these tests were analyzed with the objectives of comparing grain-yield-related variables of recently registered cultivars with those of earlier cultivars and determining the yield advances made within the Canada western red spring (CWRS) wheat class. Canadian cultivars increased maximum yield potential approximately 6–9 kg ha^{-1} $year^{-1}$ during a 90 year period. Yield potential of sawfly-resistant cultivars has been increasing at a rate of 11 kg ha^{-1} $year^{-1}$, although they consistently yielded less than the highest-yielding hollow-stem cultivars. In general, the genetic yield increases resulted from an increase in the number of kernels produced rather than an increase in kernel size. This suggests that bread wheat grown on the prairies has been sink-limited during grain filling.

Breeding higher yielding cultivars has produced significant yield increases in developing as well as developed countries. Genetic yield potential improvement may, however, decrease yield stability (Ceccarelli and Grando, 1991; Simmonds, 1991; Calderini and Slafer, 1999) because of the complexity posed by crossover genotype interactions (Sinebo, 2004). In addition, Sinebo (2004)

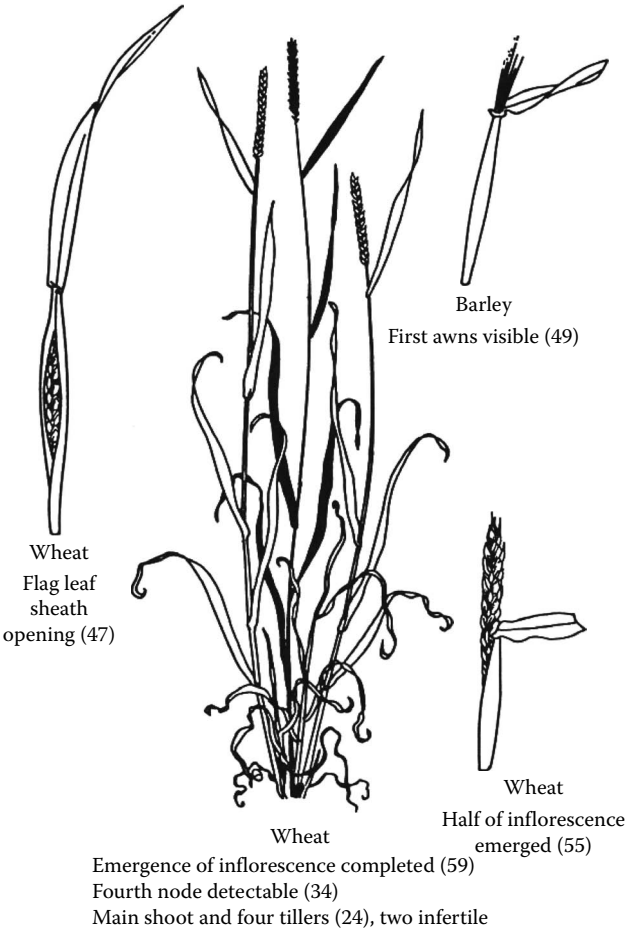

FIGURE 8.9 Booting and ear emergence in wheat and barley. (From Tottman, D.R., *Ann. Appl. Biol.*, 110, 441, 1987. With permission.)

reported that yield increases due to crop breeding for small farmers in developing countries has been slow because of complex genotype by environmental interactions and a lack of concordance between selection and target production environments. Genotype by environment interactions are commonly reported in barley, particularly in Mediterranean environments (Ceccarelli and Grando, 1991; Ceccarelli, 1994; Ceccarelli et al., 1998; Sinebo, 2004), and physiological and phenological differences are reported to be responsible for most of these interactions (Ceccarelli, 1996).

8.4 NUTRIENT REQUIREMENTS

Nutrient requirements of a crop are determined by soil, climate, yield potential of the cultivar, and cropping system. Fertilizer recommendations are usually based on results of field trials in which crop response to various rates of fertilizer application is determined. The response curve then provides, for each trial, the relationship between the amount of fertilizer and crop yield. From this curve, the economically optimum application rate of fertilizer needed for maximum yield can be derived (Neeteson and Wadman, 1987). Supply of adequate amounts of nutrients is one of the most important factors in increasing the yields of wheat and barley. It is estimated that in the 1970s fertilizers increased cereal yields in developing countries by 50% (Peter, 1980; Greenwood, 1981). Table 8.5 shows that wheat yields in India, Egypt, and Ethiopia are almost proportional to the rate of fertilizer application. Tables 8.6 and 8.7 show nitrogen, phosphorus, and potassium use for wheat

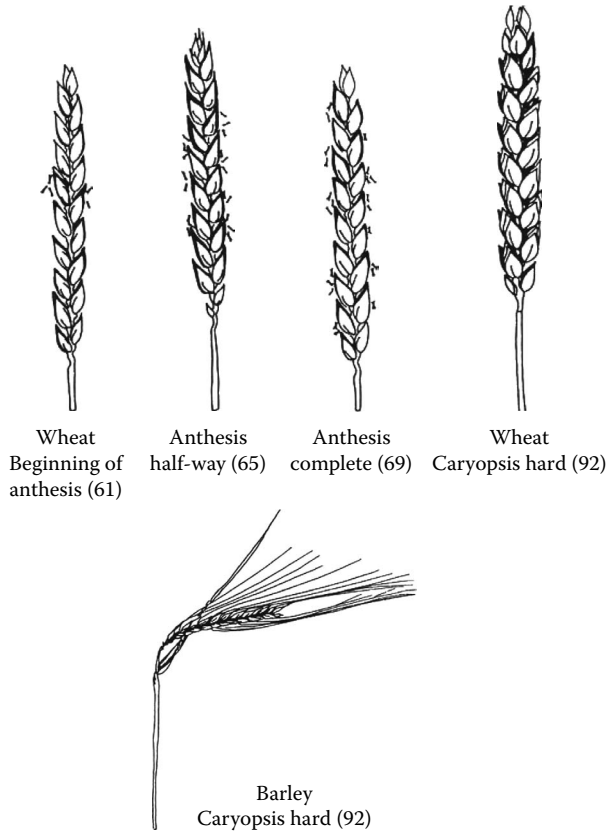

FIGURE 8.10 Anthesis and ripening growth stages in wheat and barley. (From Tottman, D.R., *Ann. Appl. Biol.*, 110, 441, 1987. With permission.)

TABLE 8.4
Growth Stages of Winter Wheat and Their Descriptions

Growth Stage	Description
0	Emergence of coleoptile.
1	Crown is visible, tillers develop.
2	Leaf sheaths elongate and form a false stem. Collars visible.
3	Culm elongation. First internode visible (jointing).
4	Tip of flag leaf visible (boot stage).
5	Peduncle elongates. Inflorescence emerges (heading).
6	Flowering (anthesis).
7	Anthesis complete. Grain filling begins. Lower leaves turn yellow color.
8	Ripening. Grain hard but will not crack.
9	Ripening. Grain hard but will not crack. Inflorescence has lost all green color. Uppermost node still green.
10	Maturity. Grain cracks and is easily separated from chaff.

Source: Waldren, R.P. and Flowerday, A.D., *Agron. J.*, 71, 391, 1979. With permission.

TABLE 8.5
Wheat Yield in Relation to Fertilizer Use in Different Countries

Country	NPK Applied (kg ha^{-1})	Grain Yield (Mg ha^{-1})
Egypt	176	3.33
Ethiopia	2	1.07
India	20	1.39

Source: Adapted from Peter, A.V., *Proc. Fert. Soc. Lond.*, 188, 1, 1980.

TABLE 8.6
Nitrogen, Phosphorus, and Potassium Application Rates (kg ha^{-1}) for Wheat in Different Countries[a]

Country	N	P	K	Total
Algeria	14	13.11	0	27.11
South Africa	20	19.23	10.79	50.02
Cyprus	60	13.11	0	73.11
Oman	84	18.35	34.86	137.21
Egypt	182	15.73	0	197.73
Zimbabwe	194	6.56	10.79	211.35
Saudi Arabia	306	121.48	0	427.48
Ecuador	7	7.43	0	14.43
Uruguay	39	13.55	0	52.55
Argentina	8	3.06	0	11.06
Brazil	9	22.72	45.96	77.68
Colombia	39	24.47	39.01	102.48
Australia	13	9.61	0	22.61
Turkey	44	11.36	0	55.36
Spain	46	9.61	9.96	65.57
Italy	83	29.72	18.26	130.98
Bulgaria	138	53.31	29.88	221.19
Sweden	124	13.55	19.92	157.47
Germany	140	26.22	49.80	216.02
The United Kingdom	186	22.72	42.33	2151.05
France	156	31.90	64.74	252.64
Ireland	153	44.14	176.79	373.93
Denmark	183	17.48	34.86	235.34
Hungary	155	38.46	79.68	273.14
Japan	176	65.98	121.18	363.16
The United States	50	9.61	9.96	69.57
Canada	50	17.48	4.15	71.63

Source: Compiled from Martinez, A., Fertilizer use statistics and crop yields, Technical Bulletin T-37, International Fertilizer Development Center, Muscle Shoals, AL, 1990.

[a] Values correspond to the 1986/1987 cropping year.

TABLE 8.7
Nitrogen, Phosphorus, and Potassium Application Rates (kg ha^{-1}) for Barley in Different Countries[a]

Country	N	P	K	Total
South Africa	22	19	11	52
Colombia	21	21	34	76
Ecuador	4	5	1	10
Uruguay	78	37	0	115
Cyprus	45	13	0	58
Saudi Arabia	56	19	0	75
Turkey	26	7	0	33
Hungary	90	29	65	184
Denmark	139	17	39	195
France	138	38	80	256
Federal Republic of Germany	105	26	66	197
Ireland	103	35	119	257
Spain	42	9	10	61
Sweden	73	12	24	109
The United Kingdom	99	16	35	150
Australia	9	9	0	18

Source: Compiled from Martinez, A., Fertilizer use statistics and crop yields, Technical Bulletin T-37, International Fertilizer Development Center, Muscle Shoals, AL, 1990.

[a] Values correspond to 1986/1987 cropping years.

and barley crops in different countries. Yields of these two crops are generally higher where higher levels of N, P, and K nutrients are applied (Martinez, 1990).

Nitrogen represents one of the most important and expensive inputs in wheat and barley production (Otteson et al., 2007, 2008). Current nitrogen use efficiency is estimated to be only 33% in wheat (Mullen et al., 2003). However, field trials in Europe have recorded an average 50%–60% recovery of N fertilizer applied to winter wheat (in grain and straw) (Blankenau et al., 2002; Macdonald et al., 2002). Lopez-Bellido et al. (2006) reported N recovery efficiency of durum wheat ranges from 32% to 54% depending on the year of cultivation. Wuest and Cassman (1992) reported that the recovery of N applied at planting ranged from 30% to 55%, while recovery of N applied at anthesis ranged from 55% to 80%. Sowers et al. (1994) found that more ^{15}N-labeled fertilizer was recovered with split application than with fall-applied N. Hence, a large part of fertilizer N is not recovered in crop yields (Otteson et al., 2007).

Efficient use of N in the crops requires that adequate amounts of other nutrients, especially P, K, and S, are also available (Hussain and Leitch, 2008). On average, each kilogram of S that a crop needs but cannot take up reduces N uptake by 15 kg. The N that is not taken up remains in the soil and can be lost through runoff, deep percolation, or denitrification (Schnug and Haneklaus, 1994). The bread-making quality of wheat may also depend on the N:S ratio in the grain (Gooding and Davies, 1992).

Nitrogen fertilizer use efficiency by winter wheat is highest when fertilizer applications are timed to coincide with high crop demand for N. Winter wheat N uptake is most rapid from the tillering through the booting growth stages, with 80% of the total accumulation occurring before

grain filling (Knowles et al., 1994). Darwinkel (1983) reported that N demand increases sharply just before onset of stem elongation, the most rapid phase of crop growth.

Hatfield and Prueger (2004) reported that N fertilizer consumption did not change significantly in Western Europe or in the United States from 1978 until 2000, whereas at the same time the nitrogen use efficiency of cereals decreased (Muurinen et al., 2007). This observation combined with available information demonstrating wheat yields leveling off in the 1990s (Slafer and Peltonen-Sainio, 2000) sets high demands on plant breeding to develop cultivars with increased yield potential associated with higher nitrogen use efficiency.

Nitrogen use efficiency of preplant vs. spring N fertilizer applications have been compared for winter wheat grown in rainfed regions of the United States. Lutcher and Mahler (1988) found that applications of N fertilizer through the jointing (Feekes stage 6) growth stage (Large, 1954) gave maximum wheat grain yields. They also found lower wheat grain yields with N applied after booting (Feekes stage 10). Lutcher and Mahler (1988) spring topdressed 101 kg N ha^{-1} as either ammonium nitrate or urea ammonium nitrate (UAN, 32% N solution) on winter wheat from early tillering (Feekes 4) through booting on a silt loam soil in Idaho. They found that maximum grain yields were produced from both N forms applied until jointing; however, a decline in yield resulting from their late spring application was less for UAN than for ammonium nitrate.

The response of spring wheat to N fertilizer also varies with rate and timing of application relative to plant development (Mossedaq and Smith, 1994; Otteson et al., 2008). Mossedaq and Smith (1994) reported that N demand for wheat increases sharply just before stem elongation (Feeks stage 5), the most rapid phase of crop growth. Lopez-Bellido et al. (2005) reported that N use efficiency in wheat was higher when fertilizer was applied in spring before stem elongation rather than in autumn, before sowing. However, supplying N in two or three applications in spring is a common fertilizer recommendation to increase N use efficiency in temperate Europe (Limaux et al., 1999; Arregui and Quemada, 2008). Figure 8.11 shows a quadratic relationship between rates applied and N uptake by wheat grains. Estimated maximum N uptake occurred at 183 kg N ha^{-1}. Nitrogen fertilizer rate recommendations for wheat in the Southern United States are generally 134 kg N ha^{-1}, which should be applied at growth stage GS 25 and/or 30 (Zadoks et al., 1974; Farrer et al., 2006).

After nitrogen, phosphorus deficiency is the most widespread nutrient deficiency in wheat and barley throughout the world. Crop phosphorus requirements should be determined on the basis of soil test P and crop yield response.

Different mathematical methods can be used to determine the optimum rate of fertilizer application. For example, when the critical level of soil test P for wheat was evaluated, an exponential function gave results similar to those found with the linear-response-and-plateau function

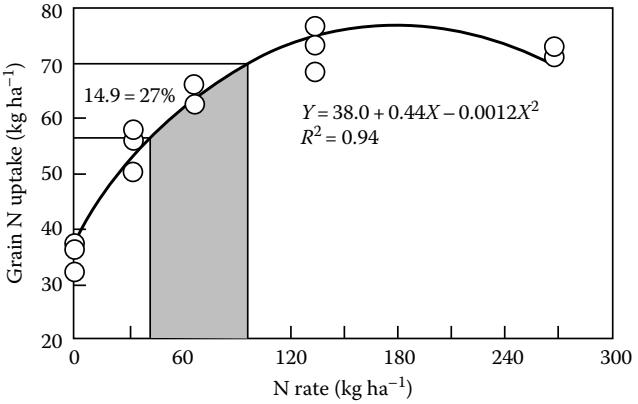

FIGURE 8.11 Relationship between nitrogen rates and N uptake by wheat grains. (From Raun, W.R. and Johnson, G.V., *Agron. J.*, 87, 827, 1995. With permission.)

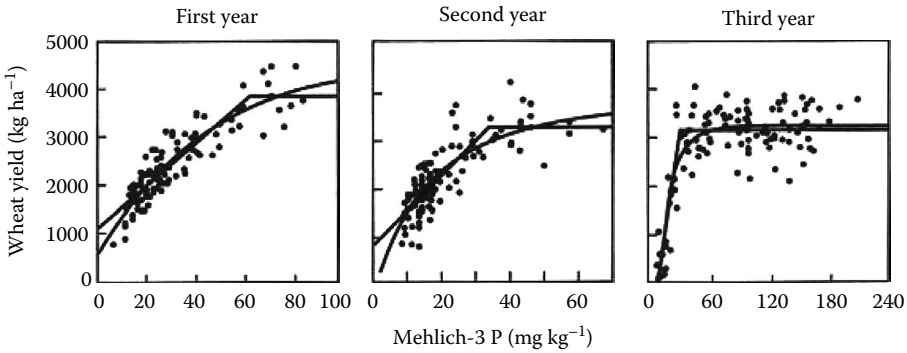

FIGURE 8.12 Response of wheat to Mehlich-3 extractable P with linear-plateau and exponential prediction functions for three crops. (From Cox, F.R., *Soil Sci. Soc. Am. J.*, 56, 1504, 1992. With permission.)

(Figure 8.12). The critical level over 3 years ranged from 31 to 47 mg extractable P kg^{-1} with a mean of 39. This value is similar to the average critical value for corn (38 mg kg^{-1}) and somewhat more than that for soybean (36 mg kg^{-1}) using the economic optimum approach. The much wider range in critical levels found when arbitrarily using 95% maximum yield with the exponential function indicates that economic conditions can have a major effect on the critical level interpretation, and should be considered.

Genotypic differences have been observed for P requirements of wheat. A greenhouse study in Brazil indicated that root length, root dry weight, and P use efficiency were different among genotypes (Table 8.8). Phosphorus concentrations in shoots did not differ significantly among genotypes across the three P levels, but root length varied from 32.7 to 44 cm, root dry weight varied from 0.41 to 0.54 g pot^{-1}, and P use efficiency varied from 125 to 188 mg dry matter mg P^{-1} absorbed. Based

TABLE 8.8
Root Length, Root Dry Weight, P Concentration in Shoot, and P Use Efficiency of 15 Wheat Genotypes Across Three P Levels

Genotype	Root Length (cm)	Root Dry Weight (g pot^{-1})	P Concentration in Shoot (g kg^{-1})	P Use Efficiency (mg DM mg P Absorbed^{-1})
1. Anahuac	39.8abc	0.42	3.33	152ab
2. BR10	40.0abc	0.50	3.11	188a
3. BR26	43.2ab	0.44	3.26	152ab
4. BR33	41.1abc	0.42	3.54	138ab
5. PF87949	38.0abc	0.48	3.36	185a
6. PF87950	37.2abc	0.52	3.26	150ab
7. PF89481	41.7ab	0.42	3.34	168ab
8. PF89490	39.7abc	0.43	3.10	182a
9. CPAC8909	35.7abc	0.41	3.31	183a
10. CPAC8947	35.2bc	0.42	3.27	143ab
11. CPAC89128	32.7c	0.54	3.12	182a
12. CPAC89194	41.3abc	0.44	3.13	125b
13. CPAC89321	41.5ab	0.41	3.30	145ab
14. IAPAR8745	44.0a	0.51	3.21	152ab
15. NL459	42.8ab	0.47	3.85	162ab

Note: Means in the same column followed by the same letter are not significantly different at 5% probability levels by Tukey's test.

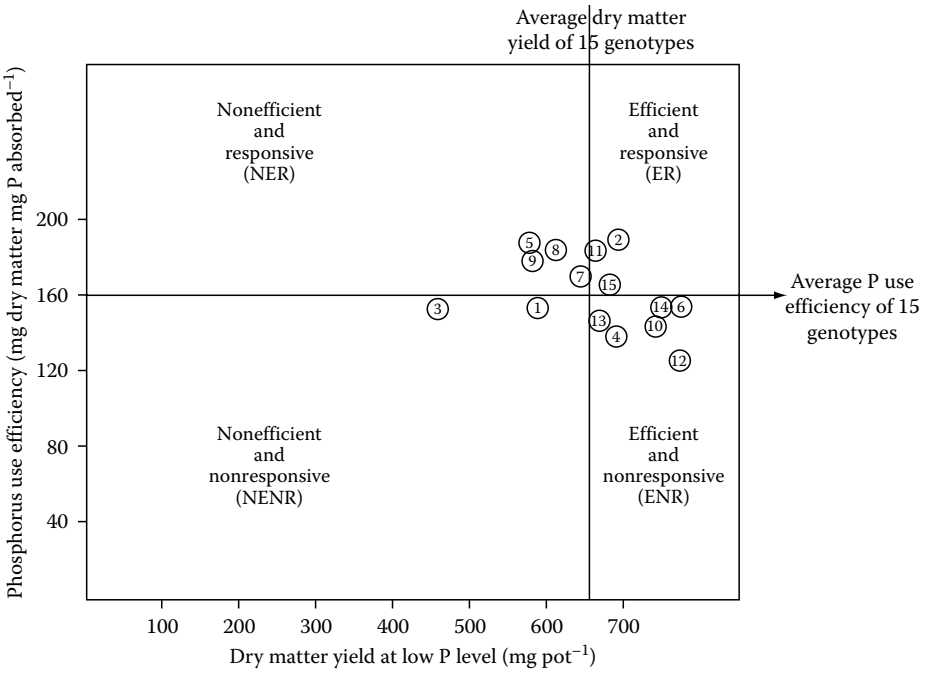

FIGURE 8.13 Classification of wheat genotypes for P use efficiency. Numbers in the circles correspond to genotypes listed in Table 8.8.

on P use efficiency, genotypes were classified into four groups, as shown in Figure 8.13. This type of grouping was suggested by Fageria and Baligar (1993) for crop genotypes for P use efficiency. The first group was genotype efficient and responsive (produced above the average yield of all the genotypes and responded well to applied P). The second classification was genotype efficient and nonresponsive (produced more than average yield, but response to P application was lower than the average of all genotypes). The third type of genotype was nonefficient and responsive (produced less than average dry matter yield but responded to P application). The last group of genotypes produced less than average yield, and response to applied P was also less than average. This type of genotype was classified as nonefficient and nonresponsive. From a practical point of view, the genotypes that fall into the group efficient and responsive are the most desirable. Because these genotypes produced well at a low P level and also responded well to applied P, suggesting that this type of genotype can be utilized under low as well as high technology with reasonably good yield.

Phosphorus uptake in roots and dry weights of roots of efficient and responsive genotypes were superior to those of nonefficient and nonresponsive genotypes. Other plant characteristics such as root length and P concentration were similar, but all the efficient and nonresponsive genotypes produced higher shoot weights and shoot P uptake than nonefficient nonresponsive genotypes. This means the greater P efficiency was attributed to greater P use efficiency than to differences in P concentration. Gardiner and Christensen (1990) reported similar results for wheat cultivars in relation to P use efficiency.

Data related to nutrient uptake by wheat and barley in tropical and subtropical climates are presented in Table 8.9. When 8 tons ha^{-1} dry matter (grain + straw) of wheat was produced, the uptake of N was 125 kg ha^{-1}, of K was 92 kg ha^{-1}, and of P was 22 kg ha^{-1}. A barley grain yield of 5.4 tons ha^{-1} resulted in uptake of 168 kg N ha^{-1}, 139 kg K ha^{-1}, and 27 kg P ha^{-1} in both grain and straw combined. Most of the N and P were translocated to the grain, while most of the K remained in the straw. Halvorson et al. (1987) reviewed the literature and concluded that the amount of N needed by a wheat crop (roots, vegetative portion, and grain) ranged from 30 to 50 kg N ton^{-1} of grain in various parts of the United States. In the case of barley, approximately 1 kg of N is required for each 34 kg of grain produced (McGeorge, 1953; Jensen and Lund, 1967). Muurinen et al. (2006) reported

TABLE 8.9
Uptake of Macronutrients by Wheat and Barley[a]

Crop		Yield (t ha^{-1})	Nutrient (kg ha^{-1})					
			N	P	K	Ca	M	S
Wheat	Grain	3	75	15	12	3	9	5
	Straw	5	50	7	80	13	5	9
	Total	8	125	22	92	16	14	14
	ER—grain		40	200	250	1000	333	600
	ER—straw		100	714	63	385	1000	556
Barley	Grain	5.4	123	20	32	—	9	11
	Straw	—	45	7	107	—	10	11
	Total		168	27	139	—	19	22
	ER—grain		44	270	169	—	600	491

Sources: Malavolta, E., Potassium, magnesium and sulphur in Brazilian soils and crops, Technical Bulletin 4, Potash and Phosphate Institute, Piracicaba, Brazil, 1979; Munson, R.D., Potassium, calcium, and magnesium in the tropics and subtropics, Technical Bulletin T-23, International Fertilizer Development Center, Muscle Shoals, TN, 1982.

Note: Nutrient uptake = concentration × dry matter.

[a] Nutrient efficiency ratio (ER) = yield kg^{-1} nutrient uptake.

that the N use efficiency in wheat (kg grain kg N^{-1} applied) was 29.4 kg kg^{-1} in the Nordic region (Denmark, Finland, Norway, and Sweden). Similarly, Ortiz-Monasterio et al. (1997) reported that in wheat nitrogen use efficiency (kg grain kg N^{-1} applied) varied from 26 to 44 kg kg^{-1} under different growing conditions. Muurinen et al. (2006) reported that the nitrogen use efficiency in barley (kg grain kg N^{-1} applied) was 32.8 kg kg^{-1} in the Nordic region.

It has been estimated that P is inadequate for maximum crop production in nearly 67% of cultivated soils, causing an important constraint to crop production (Batjes, 1997; Ozturk et al., 2005). Phosphorus efficiency is low, and only about 15%–20% of the applied P is used by the first crop. Most of the P applied to soils to meet P demand of plants is converted into unavailable forms of P that cannot be easily taken up by plant roots. Development of P-efficient genotypes is an important strategy for crop production on P-deficient soils (Ozturk et al., 2005; Fageria, 2009). Phosphorus requirements are estimated for vegetative and grain portions of the wheat plant to be from 6 to 8 kg P ton^{-1} of grain (Halvorson et al., 1987). Parson et al. (2007) reported that wheat uptake of P was significantly affected by soil fertility, with the highest uptake of P occurring when N and K fertility were also adequate. Potassium removal in wheat grain is about 5 kg ton^{-1} of grain. At harvest, the dry matter of cereal crops grown with adequate nutrients seldom contains less than 1.5% N, 0.30% P, and 1.5% K (Greenwood et al., 1980a,b,c). The Food and Agricultural Organization (FAO) carried out more than 100,000 fertilizer trials with indigenous cereal varieties and cultural practices of 40 developing countries and concluded that usually 10–20 kg of grain was produced for every kilogram of N applied when growth was limited by N. The corresponding values for P and K were 20–25 and 3–5 kg cereal grain produced kg^{-1} of nutrient applied, respectively (Peter, 1980; Greenwood, 1981). Mazzoncini et al. (2008) reported that wheat produced 34 kg grain for each kilogram of N accumulated in the straw and grain and 197 kg grain for each kilogram P in the grain plus straw. The nutrient requirements of a crop can be estimated from shoot nutrient uptake with the following formula:

$$N_R = \frac{Y_u - X_u}{E_f}$$

where

N_R is the nutrient requirement

Y_u is the uptake of nutrient in the aboveground dry matter to attain the desired yield

X_u is the uptake of nutrient from the soil without fertilizer addition

E_f is the increase in nutrient uptake of aboveground dry matter per unit of nutrient applied

The nutrient uptake and yield relationship is shown in Figure 8.14.

Micronutrient-deficient soils are widespread; many millions of hectares of arable land worldwide are deficient in one or more micronutrient elements (Welch et al., 1991; Sarkar et al., 2007; Genc et al., 2009). For example, Zn deficiency was reported for soils of various characteristics: high and low pH, high and low organic matter, calcareous, sodic, sandy, wetland or ill-drained, and limed acid soils (Takkar and Walker, 1993; Rengel and Graham, 1995).

Large areas of the Australian cereal belt are deficient in micronutrients, notably Zn and Mn, and wheat (*Triticum aestivum*) grown under such deficient conditions produces seed with low Zn or Mn concentrations (Graham et al., 1992). When seed with low Mn content was resown in Mn-deficient soil (as is commonly done by Australian farmers), wheat had a poor seedling vigor and low yields at harvest (Singh and Bharti, 1985; Marcar and Graham, 1986). Similar results were obtained with *Hordeum vulgare* where elevated Mn content in seed increased both vegetative and grain yield under Mn-deficient conditions in the field (Longnecker et al., 1991). Wide variation in Zn and Mn use efficiency has been observed in cereals, including wheat and barley (Graham et al., 1992; Genc et al., 2002, 2003, 2006, 2009; Sadana et al., 2002; Hebbern et al., 2005). In the last few decades, a major focus of breeding has been to improve the grain Zn and Fe concentration of staple food crops as a means of overcoming chronic nutrient deficiencies that afflict large numbers of people in developing countries (Cakmak et al., 1996, 1997, 1998, 1999; Cakmak, 2008).

Grain Zn concentration in a bread wheat population showed continuous variation, suggesting that it is a quantitative trait controlled by several genes (Shi et al., 2007). Nutrient efficiency and grain nutrient loading are considered to be under separate genetic control (Cakmak et al., 2004), although there has been no systematic genetic analysis of the relationship between these traits (Genc et al., 2009). While plant nutrient uptake may not be directly related to grain nutrient levels, without an adequate pool of Zn and Fe in the vegetative tissue, grain Zn and Fe concentrations may be low, irrespective of the degree of remobilization of nutrients and loading into the grain (Genc et al., 2009).

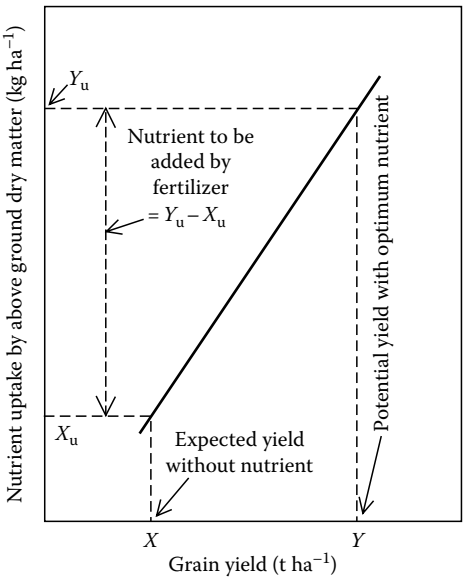

FIGURE 8.14 Nutrient uptake and yield relationship used to calculate nutrient requirements in crop plants.

Evidence of this is seen in the large increases in grain Zn concentrations that can be achieved from foliar applications of Zn prior to grain filling (Cakmak, 2008; Peck et al., 2008).

8.4.1 Nutrient Concentration

The determination of nutrient concentrations in the plant is an important tool for assessing plant nutrient status. Plant tissue analysis is often used to complement soil test analyses for diagnosing nutrient deficiency or sufficiency in crops. Plant tissue analyses measure nutrients that have been absorbed by plants, and they are considered a reliable indicator of the soil nutrient fraction available to plants (Bolland and Paynter, 1994; Hocking, 1994; Elliott et al., 1997; Grant et al., 2001; Rashid et al., 2005; Ziadi et al., 2008). The principles and relationships between nutrient concentrations and yields are discussed in Chapter 4. Deficient, critical, or adequate, and high levels of nutrients in wheat and barley are given in Tables 8.10 and 8.11. As discussed in Chapter 4, these values are affected by several factors, but may serve as general guidelines in the interpretation of plant analysis results. In general, deficient, adequate, and high values decrease with increasing plant age. These values are higher for leaves than for whole plant tops.

TABLE 8.10
Approximate Nutrient Concentrations in Mature Wheat Tissue That May Be Classified as Deficient, Adequate, or High

			Deficient	Adequate	High
Nutrient	**Growth Stage**	**Plant Part**		**g kg^{-1}**	
N	Tillering	Leaf blade	<38	43–52	>52
	Shooting	Leaf blade	<30	36–44	>44
	Heading	Whole tops	<15	21–30	>30
	Flowering	Leaf blade	<24	27–30	>30
P	Tillering	Leaf blade	<3.1	3.5–4.9	>4.9
	Shooting	Leaf blade	<2.8	3.2–4.0	>4.0
	Heading	Whole tops	<1.5	2.1–5.0	>5.0
	Flowering	Leaf blade	<2.2	2.5–3.4	>3.4
K	Tillering	Leaf blade	<28	34–42	>42
	Shooting	Leaf blade	<26	31–36	>36
	Heading	Whole tops	<13	15–30	>30
	Flowering	Leaf blade	<20	23–32	>32
Ca	Heading	Whole tops	<2.0	2.0–5	>5
Mg	Heading	Whole tops	<1.2	1.5–5	>5
S	Heading	Whole tops	<1.2	1.5–4	>4
				mg kg^{-1}	
Cu	Heading	Leaf blade	<1.6	>2.2	—
Zn	Heading	Whole tops	<15	15–70	>70
Mn	Mid-till-S-E[a]	Whole tops	—	11–13	—
Fe	Preheading	Upper leaf blade	—	25–100	—
B	Stem extension	Whole tops	<5	6–10	>16
Mo	Stem extension	Leaf blade	<0.05	0.05–0.1	>0.1

Sources: Ward, R.C. et al., Plant analysis as an aid in fertilizing small grains, in *Soil Testing and Plant Analysis*, Walsh, L.M. and Beaton, J.D. (eds.), Soil Science Society of America, Madison, WI, 329–348, 1973; Reuter, D.J., Temperate and sub-tropical crops, in *Plant Analysis: An Interpretation Manual*, Reuter, D.J. and Robinson, J.B. (eds.), Inkata Press, Melbourne, 38–99, 1986.

[a] Till, tillering; S-E, stem elongation.

TABLE 8.11
Approximate Nutrient Concentrations in Mature Barley Tissue That May Be Classified as Deficient, Adequate, or High

			Deficient	Adequate	High
Nutrient	**Growth Stage**	**Plant Part**		**g kg^{-1}**	
N	Tillering	Leaves	<39	47–51	>51
	Shooting	Leaves	<36	45–47	>47
	Heading	Whole tops	<15	20–30	>30
	Flowering	Leaves	<26	29–35	>35
P	Tillering	Leaves	<4.4	5.0–6.8	>6.8
	Shooting	Leaves	<3.7	4.2–4.8	>4.8
	Heading	Whole tops	<3.5	2.0–5.0	>5.0
	Flowering	Leaves	<2.7	3.1–4.2	>4.2
K	Tillering	Leaves	<35	42–47	>47
	Shooting	Leaves	<30	35–41	>41
	Heading	Whole tops	<13	15–30	>30
	Flowering	Leaves	<20	23–28	>28
Ca	Heading	Whole tops	<3.0	3–12	>12
Mg	Heading	Whole tops	<1.5	1.5–5	>5
S	Heading	Whole tops	<1.5	1.5–4	>4
				mg kg^{-1}	
Cu	Stem extension	Whole tops	<2.3	4.8–6.8	>6.8
Zn	Heading	Whole tops	<15	15–70	>70
Mn	Heading	Whole tops	<24	25–100	>100
Fe	Heading	Whole tops	—	50–100	—
B	Stem extension	Whole tops	1.9–3.5	6–10	>16
Mo	Heading	Whole tops	—	0.3–5.0	—

Sources: Ward, R.C. et al., Plant analysis as an aid in fertilizing small grains, in *Soil Testing and Plant Analysis*, Walsh, L.M. and Beaton, J.D. (eds.), Soil Science Society of America, Madison, WI, 329–348, 1973; Reuter, D.J., Temperate and sub-tropical crops, in *Plant Analysis: An Interpretation Manual*, Reuter, D.J. and Robinson, J.B. (eds.), Inkata Press, Melbourne, 38–99, 1986.

In addition to N concentration in shoot and grain, grain protein content is an important factor that influences the milling and baking quality of wheat (Woolfolk et al., 2002), and N and crop management practices are the major factors that influence grain protein concentration (Bly and Woodward, 2003; Subedi et al., 2007). Synthesis of protein in wheat grains depends on the uptake of soil N before flowering, continual uptake during the grain filling, and remobilization of stored vegetative N before flowering (Fischer, 1993). A grain protein concentration of less than 128 g kg^{-1} is considered as a reliable indicator of low N sufficiency in wheat (Selles and Zentner, 2001).

8.4.2 Nutrient Distribution in Plant Parts

Nutrient distribution in plant parts (grain and shoot) is an important determinant of grain yield and quality. For example, N uptake in grain is positively associated with grain yield of annual crops (Fageria and Baligar, 2005). Similarly, N uptake in grain is positively associated with protein content and grain quality. Efficiency of N remobilization is an important mechanism for increasing grain N content (Banziger et al., 1992). The distribution of N in plant parts is affected by genotypes

(Nagarajan et al., 1999; Przulij and Momcilovic, 2001; Emebiri and Moody, 2004), environmental conditions (Palta and Fillery, 1995; Boonchoo et al., 1998; Paynter and Young, 2004), and their interaction (Bertholdsson, 1999). Since the grain is the main sink for N after anthesis, the sources of grain N are the vegetative organs (which accumulate N prior to grain filling) and N uptake during the grain-filling period (Cox et al., 1985). Under conditions of high N and water availability, post-anthesis N uptake is about 20% of the total N uptake at maturity (Abeledo et al., 2008). However, the interaction between genetic variation in N assimilation and nutrient and water availability the crop cycle modifies the proportion of grain N that is assimilated in pre or post anthesis, and the importance of remobilization as source of N for the grain. When stress occurs during the post-anthesis period, the grain N requirement may be satisfied by N taken up during the pre-anthesis period (Abeledo et al., 2008). This N translocated from vegetative organs can provide between 60% and 95% of N in the grain at harvest (Smith and Whitfield, 1990; Palta and Fillery, 1995). In wheat, greatest differences in N economy between cultivars released during different eras were related to uptake during the pre-anthesis phase (Slafer et al., 1990; Bulman et al., 1993).

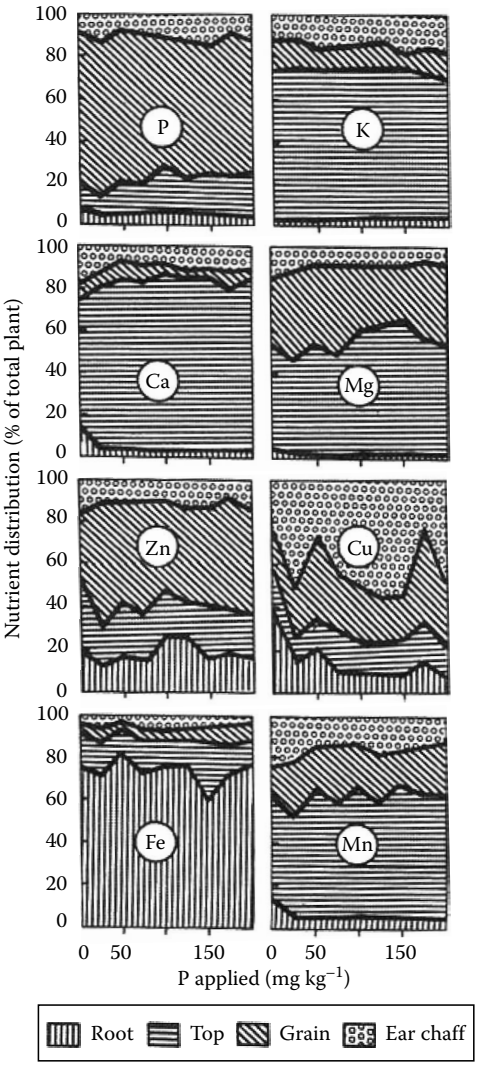

FIGURE 8.15 Distribution of nutrients in different plant parts of wheat. (From Fageria, N.K., *Pesq. Agropec. Bras.*, 25, 530, 1990.)

In wheat, plant breeders have significantly increased nitrogen harvest index (Slafer et al., 1990). Similarly, in barley, nitrogen harvest indices were 0.76 and 0.67 for new and old cultivars, respectively. Lopez-Bellido et al. (2006) reported nitrogen harvest index in durum wheat of 0.65–0.82, with an average value of 0.73 depending on N rate and timing of application. Ehdaie and Waines (2001) reported very similar values of nitrogen harvest index in durum wheat, ranging between 0.63 and 0.71. Wych and Rasmusson (1983) in the United Sates and Bulman et al. (1993) in Canada reported that modern barley cultivars showed a higher total N in the grains than their predecessors but with less variation in the nitrogen harvest index. Low N concentrations of vegetative tissues at harvest has been suggested as a selection criterion for increasing nitrogen harvest index in wheat (Cassman et al., 1992) and in barley (Przulij and Momcilovic, 2001).

The nutrient distribution in different plant parts of wheat at harvest is presented in Figure 8.15. These values were determined in a greenhouse experiment conducted in an Oxisol of central Brazil. On average, about 4% P was retained in roots, 17% in tops, 67% transported to the grain, and 12% in ear chaff. Potassium distribution in different plant parts was 2% in roots, 72% in tops, 11% in grain, and 15% in chaff. As regards Ca, 5% was in the roots, 77% in the tops, 6% in the grain, and 12% in the ear chaff. The magnesium distribution was 2% in roots, 53% in tops, 35% in grain, and 10% in chaff.

Micronutrient distribution was as follows: 18% Zn was retained in the roots, 22% in tops, 47% in grain, and 13% in ear chaff. Roots retained 15% Cu, tops 14%, grain 29%, and chaff 42%. Distribution of Fe was 73% in roots, 15% in tops, 5% in grains, and 7% in chaff. Distribution of Mn was 6% in roots, 55% in tops, 21% in grain, and 18% in ear chaff. In conclusion, roots retained maximum Fe; tops maximum K, Ca, Mg, and Mn; and grain maximum P and a considerable amount of Mg and Zn.

According to Waldren and Flowerday (1979), nitrogen uptake in winter wheat was most rapid from stage 2 to stage 4, and 80% of the total accumulation occured by stage 7 (anthesis complete). Over 70% of the total N uptake was translocated to the grain at maturity. Uptake of P and K was most rapid from jointing to the end of anthesis. Seventy-five percent of P uptake was translocated to the grain at maturity, but only 15% of K present in the plant was found in the grain at maturity. Knowles and Watkins (1931) found most of the N and P taken up by wheat plants were translocated to the grain either directly or by mobilization from other parts, but only a small amount of K was translocated to grain from other parts of the plant. A similar pattern of N mobilization was shown by McNeal et al. (1968).

8.5 SUMMARY

Wheat and barley are the world's foremost grain source for human consumption. They originated in western Asia are now grown extensively in all regions of the world except the lowland humid tropics, where foliar disease, insects, and high mean temperatures preclude successful cultivation. Both crops are adapted to daily mean temperatures in the range of 10°C–20°C. Winter wheat and barley cultivars are planted in the autumn or winter and usually require vernalization for normal phenological development. Spring cultivars are planted in the spring in temperate climates or in the winter or autumn in lower latitudes where temperatures are too high for vernalization of winter cultivars.

High-yielding semidwarf cultivars with maximum yields exceeding 10 Mg ha^{-1} have contributed to increased yields for farmers in both developed and developing countries. These cultivars normally have greater harvest indices, shorter periods from sowing to anthesis, and more grain per unit area than taller cultivars, and are more tolerant to lodging. Wheat and barley are produced under both irrigated and dryland conditions, and barley is generally recognized as having greater drought and salinity tolerance than wheat. Neither crop is adapted to acid soils, although wheat can be produced at a lower pH than barley, and some genetic tolerance to very acid soils has been identified. If commercial cultivars with tolerance to significant levels of aluminum saturation can be developed, wheat could be expanded in many cool tropical areas that have acid soils.

Nitrogen is one of the most yield-limiting nutrients for wheat and barley production under most agroecological conditions. Its N use efficiency can be improved by planting N efficient genotypes, and using appropriate N rates and timing of application. Nitrogen fertilizer applied at planting normally has lower recovery efficiency compared to that applied as topdressing during stem elongation. The N harvest index of modern wheat and barley cultivars is higher than that of the older cultivars. Modern cultivars tend to have a higher N content in ears at heading than old cultivars, and the magnitude of the differences increases with N availability. In most wheat-growing areas, nitrogen is the most limiting mineral nutrient, and 1 metric ton of wheat grain contains about 21 kg N, 4 kg P, and 4 kg K. Barley grain nutrient concentrations are often equal or slightly lower than those in wheat, and 1 metric ton removes approximately 19 kg N, 4 kg P, and 5 kg K. Because of low yields, many dryland wheat- and barley-producing areas, especially in grassland soils with large reserves of organic matter, require little fertilizer. Both soil and plant analyses can be used to diagnose and correct nutrient deficiencies and toxicities.

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9 Rice

9.1 INTRODUCTION

Rice is the most important staple food for more than half of the world's population, including regions of high population density and rapid growth (Fageria et al., 2003). It provides about 21% of the total caloric intake of the world's population. More than 90% of rice is produced and consumed in Asia. In Asia, where more than 3.1 billion people live, it provides an average 35% of the total calories consumed, ranging up to 80% in Cambodia (IRRI, 1993). It is the most important tropical cereal and, on a worldwide basis, rice production is slightly below that of corn. Rice is cultivated in 111 countries on all continents (except Antarctica), at latitudes from 36°S in Australia, to 45°N in Japan, 49°N in the Czech Republic, and similar latitudes in Hungary and in the Heilongjiang Province of China (Lu and Chang, 1980; McDonald, 1994). Rice production is concentrated in Asia, where more than 90% of the world's supply is produced. China and India are the leading producers as well as consumers of rice. Other major rice-producing countries are Japan, Thailand, Vietnam, and Indonesia.

Oryza sativa L. and *Oryza glaberrima* Steud. are cultivated species of rice. *Oryza sativa* is widely cultivated, but *O. glaberrima* is mainly grown in Africa where it is rapidly being replaced by *O. sativa*. The two species show small morphological differences, but hybrids between them are always sterile (Chang, 1976). The origin of *O. sativa* is controversial, but it is thought to have been domesticated in India or Indochina. *Oryza glaberrima* originated in Africa. A detailed description of the biosystematics and cytogenetics of the genus is given by Chang (1964) and Nayar (1973).

Oryza sativa is further divided into the japonica, indica, and javanica ecological groups. Japonica rice, adapted to cooler areas, is widely grown in temperate countries such as central and northern China, Korea, and Japan, while indica rice is widely grown in tropical regions. Both of these species can be grown in subtropical regions. Javanica rice is the tall, large, and bold grain bulu cultivar of Indonesia, but it has spread to Japan, Taiwan, and the Philippines (Yoshida, 1983).

Unhusked grain, as well as the growing crop, is known as "paddy." Husked or hulled rice, usually termed brown rice, is milled to remove the outer layers, including the aleurone layer and the germ, after which it is polished to produce white rice. Paddy, on milling, gives approximately 20% husk, 50% whole rice, 16% broken rice, and 14% bran and meal (Purseglove, 1985). The endosperm is highly digestible and nutritious and on average contains about 8% protein.

Based on land and water management, rice culture is divided into two broad groups, upland and lowland culture. Upland rice refers to rice grown on both flat and sloping fields that are prepared and seeded under dryland conditions and depend on rainfall for moisture. This is also known as dryland, rainfed, or aerobic rice. This type of rice cultivation is most common on small- and medium-size farms in South America, Asia, and Africa. Brazil is the world's largest producer of upland rice (Fageria et al., 1982; IRRI, 1984; Fageria, 2001a). On the other hand, flooded rice is grown on flat land with controlled irrigation. It is also known as irrigated, lowland, or waterlogged rice. Lowland rice may be planted by drilling the seed into dry soil, by broadcasting pre-germinated seed into flooded fields, or by planting seedlings into flooded fields by machine or by hand. Rice planted into dry soil is commonly flooded when seedlings are 25–30 days old. The water level varies from 10 to 15 cm and is maintained until 7–10 days before harvesting, though fields may be drained once or twice and then, after a few days, reflooded. About 77 million ha, 53% of the world's rice area and about 76% of the world's rice production comes from irrigated areas (Fageria et al., 2003). In much of this area, rainfall supplements irrigation water. Irrigated areas with good water control are

TABLE 9.1
Comparison of Upland and Lowland Rice Cultures

	Lowland	Upland
1.	Cultivated on leveled, bunded, undrained soils	Cultivated on undulating or leveled naturally drained soils
2.	Water supply through rainfall or irrigation	Water supply through rainfall
3.	Water accumulation in the field during major part of crop growth	No water accumulation during crop growth
4.	Reduced root zone during major part of crop growth	Oxidized root zone during crop growth
5.	Direct seeding or transplanting	Direct seeding
6.	Thin and shallow root system	Vigorous and deep root system
7.	High tillering	Relatively low tillering
8.	Short and thin leaves	Long and thick leaves
9.	Environmental conditions are stable and uniform	Environmental conditions are unstable and variable
10.	Incidence of diseases and insects low	Incidence of diseases and insects high
11.	Weeds are not a serious problem	Weeds are a serious problem
12.	Needs high input	Needs low input
13.	High cost of production	Low cost of production
14.	Stable and high yield	Unstable and low yield

suitable for growing semidwarf varieties of lowland rice that lend themselves to improved cultural practices. A small percentage of rice area in some countries consists of deep water and floating rice culture (IRRI, 1982; Santos et al., 2003). A comparison of lowland and upland rice cultures is given in Table 9.1.

An outstanding breakthrough occurred in rice cultivation with the introduction of high-yielding cultivars. In work carried out at the International Rice Research Institute (IRRI), a cross between the tall tropical cultivar "Peta" from Indonesia and the subtropical semidwarf variety "Dee-geo-woo-gen" from Taiwan produced the semidwarf IR8. IR8 produced a record grain yield of 11 Mg ha^{-1} and responded to nitrogen up to 150 kg N ha^{-1} at several locations in tropical Asia during 1966–1968 (Chang, 1976). Rice production increased by 2.3% $year^{-1}$ from 1968 to 2001 after the release of IR8 (Swaminathan, 2006). In India, rice production grew at 1.11% from 1994 to 2001 (Swaminathan, 2006). The dissemination of this improved plant type throughout Latin America was initiated in 1968 by the Colombian-based program of the Centro Internacional de Agricultura Tropical (CIAT), Federacion Nacional de Arroceros (FEDEARROZ), and the Instituto Colombiano Agropecuario (ICA) (Cuevas-Perez et al., 1995). Breeders took advantage of Colombian environmental diversity, developing materials that could be transferred to other countries through trainees who had participated in the evaluation of these materials along with CIAT scientists. This breeding approach increased national rice yields in Colombia from 1.5 Mg ha^{-1} in 1965 to 4.4 Mg ha^{-1} in 1975, and in Latin America from 1.8 Mg ha^{-1} during the period 1950–1964 to 2.3 Mg ha^{-1} in 1974 (Cuevas-Perez et al., 1995). Later estimates indicated that semidwarf cultivars contributed 20% additional rice production in Latin America in 1981 (Cuevas-Perez et al., 1995). Scientists at IRRI and several national breeding programs combined most of the desired features in the improved plant type, including reduced plant height (to about 100 cm), erectness, short, dark-green leaves, more tillers, stiff culms, early maturity, photoperiod insensitivity, nitrogen responsiveness, and high harvest index. The widespread adoption of IR8 and other high-yielding cultivars like IR20 and IR22 made it possible for the semidwarf varieties to become major cultivars in Brazil, Colombia, Peru, Ecuador, Cuba, Mexico, Indonesia, Malaysia, Philippines, India, Pakistan, Bangladesh, and South Vietnam. By 1972–1973, high-yielding semidwarf varieties occupied a large part of the area planted to rice—about 10% of the world total and 15% in tropical Asia (Chang, 1976). At present, high-yielding semidwarf cultivars predominate in most lowland rice-producing areas worldwide. Work is in progress at IRRI and

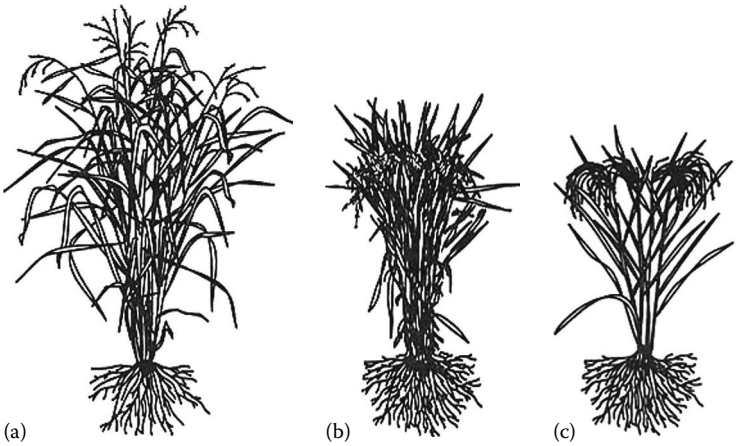

FIGURE 9.1 (a) Traditional old, (b) modern high-yielding, and (c) future ideotype plants of lowland rice. (From Kush, G.S., Increased genetic potential of rice yield: Methods and perspectives, in *Rice in Latin America: Perspectives to Increase Production and Yield Potential*, Pinheiro, B.S. and Guimarais, E.P. (eds.), EMBRAPA-CNPAF, Goiania, Brazil, Document No. 60, 13–29, 1995.)

at many national research centers to further improve plant type, grain quality, and pest resistance. Figure 9.1 shows the development of modern high-yielding rice cultivars from traditional old cultivars, as well as the rice plant ideotype of the future.

Maximum reported rice yields range from 11 to 13 Mg ha^{-1} in India and at IRRI (Swaminathan, 2006). Worldwide, average rice yields are highest in Australia, with yields in New South Wales averaging 8.9 Mg ha^{-1} in 1991–1992 (Beecher et al., 1994). These high yields have been attributed to the absence of serious pests and diseases, high solar radiation, high-yielding varieties, and planting rice in rotation with legume-based pasture (Beecher et al., 1994). However, the climate-adjusted average yield potential in most areas is about 8 Mg ha^{-1} for inbred cultivars and 8.8 Mg ha^{-1} for hybrids in the intensive double cropping systems (Swaminathan, 2006). However, the gap between potential and actual yields is large in most rice farming systems. The present world average yield is just 40% of what could be achieved with currently available technologies. This is because of imperfect varietal adaptation to local environments, insufficient nutrients, and poor control of water, pests, diseases, and weeds (Swaminathan, 2006).

In order to keep pace with population in countries where rice is the main food crop, production must increase 65% between the year 1990 and the year 2020 (IRRI, 1989; Fageria, 2007). This production increase will have to come from the same or an even less land, and water and other production inputs will have to be used more efficiently in the future. Better understanding of the growth and development of rice, as well as the effects of environmental factors such as climate, soil, nutrients, and pests, will be needed to achieve these goals. These aspects of rice production are discussed in this chapter.

9.2 CLIMATE AND SOIL REQUIREMENTS

Rice is widely distributed throughout the tropical, subtropical, and temperate zones of all continents. Temperature, solar radiation, and rainfall strongly affect rice growth and yield. Table 9.2 shows the minimum, optimum, and maximum temperatures for rice growth at different stages. Depending on growth stage, injury to rice may occur when the daily minimum temperature drops below 20°C. Rice is most sensitive to low temperature 14–7 days before heading and at flowering (Satake, 1976; Yoshida, 1983). Low temperatures at these critical stages cause a high percentage of spikelet sterility. Table 9.3 shows the effect of minimum temperatures (15°C or 19°C) around (15 days before to 15 days after) flowering on three Brazilian upland rice cultivars in a greenhouse experiment. When the

TABLE 9.2
Minimum, Optimum, and High Temperatures for Rice Growth at Different Stages

	Critical Temperature (°C)		
Growth Stage	**Low**	**Optimum**	**High**
Germination	10	20–35	45
Seedling emergence and establishment	12–13	25–30	35
Rooting	16	25–28	35
Leaf elongation	7–12	31	45
Tillering	9–16	25–31	33
Initiation of panicle primordium	15	25–30	35
Panicle differentiation	15–20	25–28	38
Anthesis	22	30–33	35
Ripening	12–18	20–25	30

Sources: Compiled from Yoshida, S., *Fundamentals of Rice Crop Science*, IRRI, Los Banos, Philippines, 1981; Fageria, N.K., *Tropical Soils and Physiological Aspects of Crop Yield*, EMBRAPA-CNPAF, Brasilia, Brazil, 1989; Fageria, N.K. and Gheyi, H.R., *Efficient Crop Production*, Federal University of Paraiba, Campina Grande, Brazil, 1999.

TABLE 9.3
Effect of Temperature on Grain Yield and Spikelet Sterility in Three Brazilian Upland Rice Cultivars

Cultivar	Minimum[a] (°C)	Maximum[a] (°C)	Grain Yield (g Pot^{-1})	Grain Sterility (%)
IAC 25	15	30	3.45	96
	19	27	26.00	9
IAC 164	15	30	5.56	97
	19	27	29.54	19
IAC 165	15	30	7.37	97
	19	27	30.73	15

Source: Fageria, N.K., *Fertilization and Mineral Nutrition of Rice*, EMBRAPA-CNPAF/Editora Campus, Rio de Janeiro, Brazil, 1984a.

[a] Minimum and maximum temperature values were observed about 1 month around flowering.

temperature was 15°C for 1 month around flowering, yield was reduced significantly in all cultivars due to very high grain sterility. Little sterility was observed at 19°C for the same growth stage.

Solar radiation is an important climatic factor that affects temperature, evapotranspiration, and photosynthesis of rice. The solar radiation requirements of rice differ from one growth stage to another (Yoshida and Parao, 1976; Fageria, 2007, 2009). Yield is significantly reduced if sufficient solar radiation is not received during the reproductive (panicle initiation to flowering) and ripening (flowering to maturity) growth stages. During reproductive growth, insufficient solar radiation reduces the number of spikelets and consequently grain yield. During the grain-filling stage, the percentage of filled spikelets is reduced by low solar radiation. Inadequate light during the vegetative growth stage affects yield and yield components only slightly (Yoshida and Parao, 1976; Fageria, 2007). A solar radiation of 300 cal cm^{-2} day^{-1} during the reproductive stage allows yields of

5 Mg ha^{-1} (Yoshida and Parao, 1976). Less solar radiation is required during grain filling to achieve the same yield level. The effects of solar radiation are generally more pronounced if potential yields are higher than 5 Mg ha^{-1} under tropical and subtropical environments.

Rice is a semiaquatic plant that is commonly grown under flooded conditions. However, about half of the rice area in the world does not have sufficient water to maintain flooded conditions, and yield is reduced to some extent by drought, defined here as a period of no rainfall or no irrigation that affects crop growth (Hanson et al., 1990). The studies of the constraints to rice yield have confirmed that water deficit is the most serious factor limiting production (Widawsky and O'Toole, 1990). One-half of global rice land and two-thirds of the rice land in South and Southeast Asia is cultivated under rainfed conditions (Huke, 1982). In addition, much of the rice land classified as irrigated is subject to periodic water deficits (Kush, 1984) due to inequitable water distribution systems and deforestation-related reduction in the water yield of many surface irrigation systems.

The evapotranspiration of upland rice increases with increasing plant age, with a maximum in the reproductive stage followed by a decrease during the ripening stage. Water stress during the growth period adversely affects growth, but the magnitude of growth reduction varies from one growth stage to another (Figure 9.2).

Rice's response to water stress at the vegetative stage has been reported primarily in terms of reduced height, tillers, and leaf area (IRRI, 1975), while at more sensitive reproductive stages, such as flowering, high spikelet sterility results in the greatest reduction in grain yield (Fageria, 1980; Cruz and O'Toole, 1984). The most critical water deficit stage is the period from about 10 days before flowering to flowering (Matsushima, 1962). High sterility resulting from water stress at this time is irreversible, and adequate water at later stages is totally ineffective in reducing its effects. If water stress occurs during the early vegetative stage, however, plants can recover.

Areas designated as "drought prone" in the classification of rainfed rice environments (Garrity et al., 1986) are widespread geographically in Asia, Africa, and Latin America. The assessments of rice breeding priorities target drought tolerance as one of the major targets (Garrity and O'Toole, 1994). The most effective method of minimizing the adverse effect of drought is for the crop to grow during the period of high rainfall and high soil water availability, i.e., to escape the drought period. Crop duration is important in determining grain yield because early maturing cultivars often escape a terminal stress while late maturing cultivars may be affected by it. The timing of drought during the

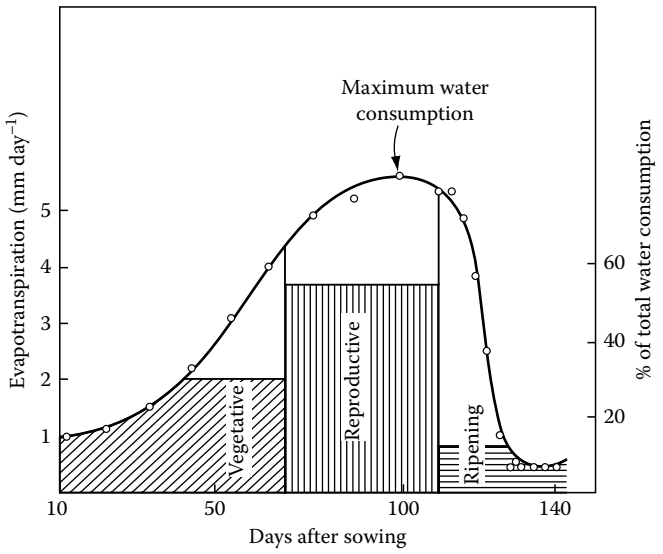

FIGURE 9.2 Evapotranspiration and water consumption during growing season of upland rice in central Brazil. (From Fageria, N.K., *Pesq. Agropec. Bras.*, 15, 259, 1980.)

growing season is also important. It is well known that the period from panicle development to anthesis is the growth stage most susceptible to water stress in rice (O'Toole, 1982). Boonjung (1993) has shown that grain yield decreases at the rate of 2% day^{-1} delay as a 15 day stress period (morning leaf water potential less than −1.0 MPa) occurs later during panicle development. Assuming a reduction of 2% grain yield day^{-1} with the delay in termination of a 15 day stress, a 20 day difference in flowering time between two cultivars of equal yield potential could cause a grain yield difference of about 40%. Thus, it is likely that cultivars with different phonological development will react differently to a drought, depending on the timing of stress (Maurya and O'Toole, 1986). These results suggest that genotypes within the same maturity group should be compared when evaluating germplasm for drought resistance/susceptibility (Garrity and O'Toole, 1994). Alternatively, it is possible in some experiments to vary planting dates so that all lines flower at about the same time (Lilley and Fukai, 1994).

Several other drought-resistance mechanisms, and traits that affect them, have been identified for rice. For upland conditions, a deep root system with high root length density at depth is useful in extracting soil water, but it does not appear to offer much scope for improving drought resistance in rainfed lowland rice where the development of a hard pan may prevent deep root penetration. Under water-limiting environments, genotypes that maintain the highest leaf water potential generally grow best, but it is not known if genotypic variation in leaf water potential is solely caused by root factors. Osmotic adjustment is promising because it can potentially counteract the effects of a rapid decline in leaf water potential, and there is large genetic variation for this trait. There is also genotypic variation in expression of green leaf retention, which appears to be a useful character for prolonged droughts, but it is affected by plant size which complicates its use as a selection criterion for drought resistance. Despite our increased understanding of stress physiology, the development of drought-resistant cultivars, i.e., cultivars that produce higher yield than others in drought conditions, has been slow in rice and other crops, largely because of large genotype by environment (G × E) interactions, which complicate the selection of drought-resistant germplasm (Fukai and Cooper, 1995).

Rice is a semiaquatic plant that can grow successfully in standing water. It can transport oxygen or oxidized compounds from the leaves to the roots and into the rhizosphere. The oxygen in the rice leaves and roots comes from atmospheric oxygen absorbed by the leaves and oxygen released in photosynthesis through the hydrolysis of water. The water requirement of rice, as measured by the transpiration ratio, is similar to that of most major crops and is mostly affected by climate and soil. The average water requirement of irrigated rice at various locations in Southeast Asia was reported to be about 1240 mm $crop^{-1}$ (Kung, 1971). Consequently, rice cultivation appears to be limited to areas where rainfall during the growing season exceeds 1000 mm or other sources of water are available (Yoshida, 1983).

Tomar and Ghildyal (1975) studied the differences in resistance to water transport between plants grown on upland soils and those grown on flooded soils. They concluded that resistance to water transport in the nonflooded rice was nearly twice as high as in the flooded plants. The nonaerenchymatous roots of nonflooded plants had about 17 times more resistance than aerenchymatous roots of flooded rice.

Rice is grown on about 150 million ha, more than 10% of the earth's arable land (Santos et al., 2003). It is adapted to a wide range of soil conditions, including sandy loams, shallow lateritic soils, and heavy clays, provided there is adequate water. The soils used for rice production worldwide are distributed over the 10 soil orders (USDA, 1975; Moormann, 1978; Hudnall, 1991). Murthy (1978) reported that the soils on which rice grows in India are so extraordinarily varied that there is hardly a type of soil, including salt-affected soils, on which it cannot be grown with some degree of success. In Brazil, flooded rice is mainly grown on Alfisols, Vertisols, Inceptisols, Histosols, and Entisols (Fageria et al., 2003). Upland rice in South America is mostly grown on Oxisols and Ultisols (Fageria, 2001a). In Sri Lanka, rice is grown on Alfisols, Ultisols, Entisols, Inceptisols, and Histosols (Panabokke, 1978). In Indonesia, the main rice soils are Entisols, Inceptisols, Vertisols, Ultisols, and Alfisols (Soepraptohardjo and Suhardjo, 1978). Raymundo (1978) reported that in the Philippines the soils used for wetland rice production are mainly Entisols, Inceptisols, Alfisols,

and Vertisols. In Europe, rice is planted on limited areas in Albania, Bulgaria, France, Greece, Hungary, Italy, Portugal, Romania, Spain, and Yugoslavia where the predominate soil orders are Inceptisols, Entisols, and Vertisols (Matsuo et al., 1978). In the United States, rice is grown primarily on Alfisols, Inceptisols, Mollisols, and Vertisols (Flach and Slusher, 1978) with small amounts produced on Histosols in Florida. Most of the soils used for rice production in the United States and some other geographic areas have properties that make them ideally suited for flood-irrigated rice. The soils are relatively young, contain significant amounts of weatherable minerals, and have relatively high base saturations despite the fact that some are in areas of high precipitation (Flach and Slusher, 1978; Fageria et al., 2003).

Soil characteristics typically associated with good rice yields include adequate soil depth, a compact subsoil horizon to retain irrigation water, good soil moisture retention, good fertility, and favorable soil structure. Clayey to loamy clay texture soils are appropriate for lowland rice production. Permeable, coarse-textured soils are less suitable for flood-irrigated rice production because they have low water or nutrient holding capacities.

Large areas of soils have the necessary characteristics and are available for conversion to rice-based cropping systems, and they could be brought into production if prices are justified. For example, in Brazil, there are about 35 million ha of poorly drained soils, known locally as "varzea," distributed throughout the country. At present less than 2 million ha of these soils are cultivated, primarily to lowland rice, during the rainy season (Fageria et al., 2003). Generally, varzea soils have good initial soil fertility, but after 2–3 years of cultivation, the fertility declines (Fageria and Baligar, 1996). With adequate fertility management, flood-irrigated rice could be grown on these poorly drained areas during the rainy seasons, with other crops grown in the dry season. Though these soils generally have an adequate natural water supply throughout the year, they are acidic and require routine applications of lime if legumes are grown in the rotation.

Rice is an acid-tolerant crop with an optimum pH for upland culture around 5–5.4 (Fageria and Zimmermann, 1996; Fageria, 2000). Data in Table 9.4 show influence of soil pH on yield and yield components of upland rice grown on a Brazilian Oxisol. However, genotype variation in soil acidity tolerance has been reported (Table 9.5). In lowland culture, soil pH rises during flooding. Increases from acidic to neutral (or slightly basic) pH are caused by reactions that reduce iron oxides and increase the concentration of carbon dioxide in the soil. Rice can also be grown on alkaline soils. It is considered moderately susceptible to soil salinity, with a threshold salinity about 3 dS m^{-1} (Maas and Hoffman, 1977).

TABLE 9.4
Grain Yield, Shoot Dry Weight, and Panicle Number of Upland Rice as Influenced by Soil pH

pH in H_2O	Grain Yield (g $Plant^{-1}$)	Shoot Dry Weight (g $Plant^{-1}$)	Panicle Number ($Plant^{-1}$)
4.6	11.00	15.91	5.00
5.7	11.53	12.96	4.58
6.2	11.73	12.24	4.50
6.4	9.49	10.62	3.92
6.6	6.83	7.78	3.42
6.8	5.15	6.03	3.25
Adequate pH[a]	5.4	5.1	5.0
R^2	0.91**	0.99**	0.94*

Source: Adapted from Fageria, N.K., *Pesq. Agropec. Bras*., 35, 2303, 2000.

[a] Adequate pH values were calculated by quadratic regression equations for each plant parameters.

*,** Significant at the 5% and 1% probability levels, respectively.

TABLE 9.5
Soil Acidity Tolerance of Upland Rice Genotypes

Genotype	High Acidity (pH 4.5 in H_2O)	Low Acidity (pH 6.4 in H_2O)
CRO97505	74.27	52.00
CNAs8983	55.23	42.93
CNAs8938	56.30	25.20
CNAs8960	51.70	47.43
CNAs8989	58.10	51.73
CNAs8817	44.90	46.60
CNAs8952	35.63	37.77
CNAs8950	40.17	26.93
BRS Primavera	53.00	47.20
Canastra	51.63	38.90
Bonança	47.80	36.53
Carisma	50.77	17.50
Average	51.63	39.22

Source: Adapted from Fageria, N.K. et al., Response of upland rice genotypes to soil acidity, in *The Red Soils of China: Their Nature, Management and Utilization*, Wilson, M.J. et al. (eds.), Kluwer Academic Publishers, Dordrecht, the Netherlands, 219–237, 2004.

9.3 GROWTH AND DEVELOPMENT

Rice is an annual grass. Irrigated rice has a seed dormancy period ranging from 1 to 3 months, depending on the cultivar and seed moisture content. The most practical method of breaking seed dormancy is a thermal seed treatment of 50°C for about 4–5 days. Normally, upland and japonica-type cultivars do not have a seed dormancy which significantly affects germination. After dormancy is broken, rice seeds sown in soil germinate in 5–7 days. The germination of rice is hypogeal. When grown in well-drained soils, the coleorhiza with the radical is the first organ to emerge; under inundation the coleoptile precedes the coleorhiza (Purseglove, 1985).

The growth cycle of the rice plant is divided into three stages: vegetative, reproductive, and spikelet filling or ripening. The yield potential of a crop is determined during these growth stages. Plant height, tillering, root growth, leaf area, and morphology are the main features of vegetative growth stage. In the reproductive growth stage, panicle initiation, booting, panicle emergence, and flowering occur during the reproductive growth stage. Panicle size or the number of spikelets per panicle is determined during the reproductive growth stage. Grain size and weight are determined during the grain filling growth stage. Reproductive growth is the stage most sensitive to biotic and abiotic stresses, followed by the grain filling and vegetative growth stages. Figure 9.3 shows growth stages of an upland rice cultivar with a growth cycle of 130 days from sowing to physiological maturity or 125 days from germination to physiological maturity under Brazilian conditions. The vegetative growth stage was 65 days long (germination to initiation of panicle primordia). The reproductive growth stage was 30 days (panicle primordia initiation to flowering), and grain filling was also 30 days long (flowering to physiological maturity). Similarly, Figure 9.4 shows growth stages of a lowland rice cultivar with a growth cycle of 140 days from sowing to maturity (135 days from germination to physiological maturity) under Brazilian conditions. The reproductive and grain filling stages are important because during these stages seed number and seed weight are determined (Fageria, 2007).

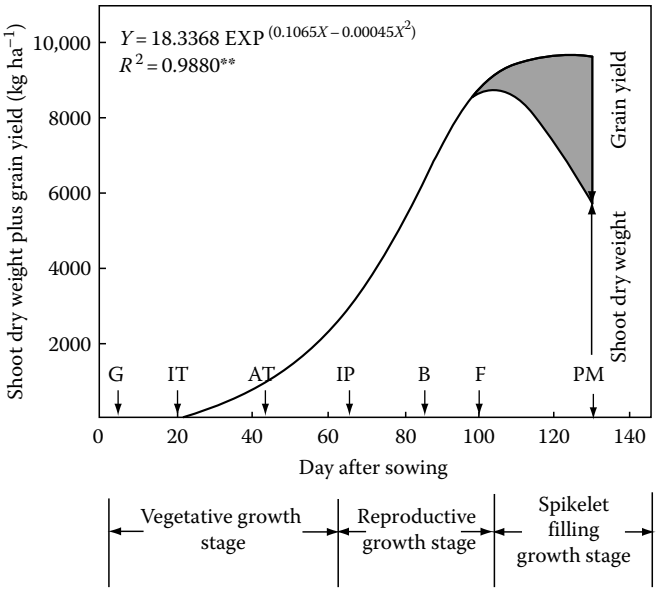

FIGURE 9.3 Shoot dry weight accumulation and grain yield of upland rice during the growth cycle of the crop in the central Brazil. G = germination, IT = initiation of tillering, AT = active tillering, IP = initiation of panicle primordia, B = booting, F = flowering, PM = physiological maturity, ** significant at the 1% probability level. (From Fageria, N.K., *J. Plant Nutr.*, 30, 843, 2007.)

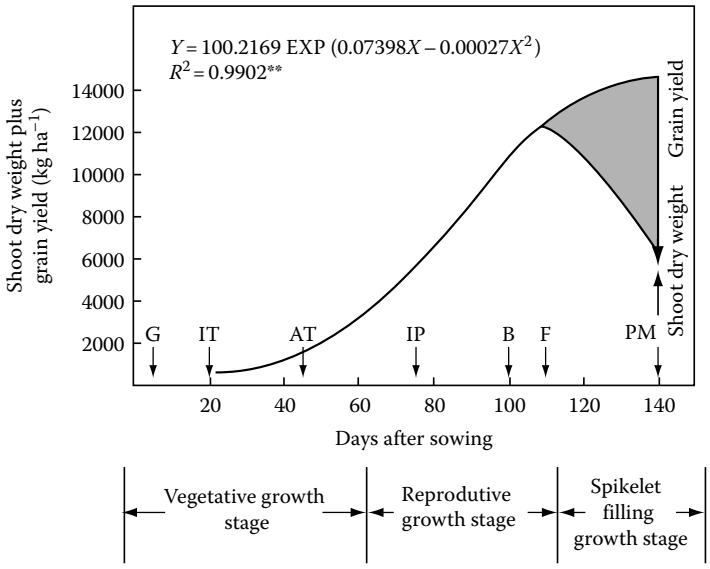

FIGURE 9.4 Shoot dry weight accumulation and grain yield of lowland rice during the growth cycle of the crop in the central Brazil. G = germination, IT = initiation of tillering, AT = active tillering, IP = initiation of panicle primordia, B = booting, F = flowering, and PM = physiological maturity, ** significant at the 1% probability level.

9.3.1 Vegetative Growth Stage

Vegetative growth extends from germination to panicle primordia initiation. The main processes that occur during this growth stage are the increase in plant height, tillering, root growth, and increasing leaf area index (LAI) and leaf weight. During the vegetative growth stage, N, P, K, and S are actively absorbed. Proteins are vigorously synthesized, leading to the acceleration of tillering and growth of leaf areas (Murayama, 1995). Tiller number affects panicle number, an important yield component that is determined during vegetative growth. The variation in the growth cycles of rice cultivars is mainly due to variation in the length of the vegetative growth stage. Under favorable tropical environmental conditions, the length of vegetative growth is about half of total growth duration (germination to physiological maturity) (Fageria, 2007). The period between the date when maximum tiller number occurs and the date of panicle primordia initiation is known as the *vegetative lag period* (Murayama, 1995).

The morphologies of upland and lowland rice seedlings at the time of tiller initiation are shown in Figures 9.5 and 9.6. The rice seedlings at this stage had four leaves, adventitious and radicle root systems, and a small tiller at the base of the main culm. The root system and the shoot of the upland rice seedling were more vigorous than those of the lowland seedling. Both seedlings were grown under similar environmental conditions, and the differences in growth rate were genetic.

Cereal seedlings initially depend totally on food mobilized from the endosperm, then pass through a transition phase when photosynthesis commences while endosperm mobilization continues. Rice seedlings become autotrophic at the 3–4 leaf stage, about 14–22 days after emergence (Salam et al., 1997). The timing of upland rice growth stages is given in Table 9.6.

9.3.1.1 Plant Height

For seedlings or juvenile plants, plant height is the distance from ground level to the tip of the tallest leaf. For mature plants, it is the distance from ground level to the tip of the tallest panicle. Plant height is an important trait because it is associated with plant lodging.

Old rice varieties were normally tall and were susceptible to lodging, especially when high rates of nitrogen fertilizer were applied. Breeders began to reduce plant height of most cereals (rice, wheat, grain sorghum, and corn) during the last half of the twentieth century in order to allow

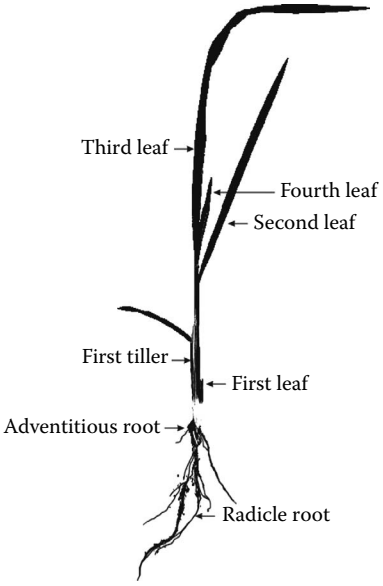

FIGURE 9.5 Morphology of upland rice seedling at tiller initiation growth stage. (From Fageria, N.K., *J. Plant Nutr.*, 30, 843, 2007.)

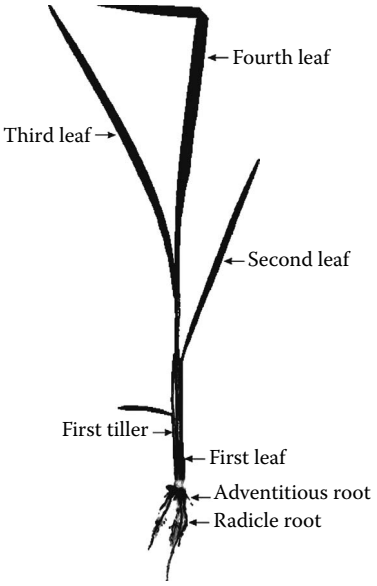

FIGURE 9.6 Morphology of lowland rice seedling at tiller initiation growth stage. (From Fageria, N.K., *J. Plant Nutr.*, 30, 843, 2007.)

TABLE 9.6
Timing (DAS, Days after Sowing) of Upland Rice Growth Stages and Definitions

Growth Stage	DAS	Definition
Germination	5	Defined as the stage when the coleoptile tip first became visible
Tillering initiation	19	Defined as the crop growth stage when first tiller from the main shoot is visible
Active tillering	45	Defined as the development stage at which maximum tillering rate per unit time during crop growth
Panicle primordia initiation	61	Defined as initiation of panicle
Booting	85	Defined as the development stage at which panicle is enclosed by the sheath of the uppermost leaf
Flowering	95	Defined as the physiological stage at which flowers are visible on the panicles
Physiological maturity	120	Defined as the growth stage at which grains are ripened and panicles are ready for harvest

Source: Fageria, N.K. et al., *J. Plant Nutr.*, 32, 2010a, in press.

application of higher rates of fertilizer without causing lodging. Although plant height of rice is influenced by environmental factors, it is genetically controlled, heritability of dwarfism is high, and it is easy to select and recombine with other traits (Jennings et al., 1979). A few dwarf segregates were so short that they are undesirable, but the great majority fell within the useful range of from 80 to 100 cm, with some reaching 120 cm (Jennings et al., 1979). During the 1960s, rice breeders made excellent progress in the development of dwarf cultivars that responded to heavy applications of nitrogen (Jennings et al., 1979). The term *Green Revolution* was associated with the development of rice cultivars with short stature (90–110 cm) that were less susceptible to lodging when heavily fertilized, especially with nitrogen (Yoshida, 1981; Fageria, 2007). In addition to lodging resistance, cultivars with short stature and sturdy culms gave higher yields at close plant spacing than taller cultivars. A marked increase in harvest index and in grain yield per day was associated

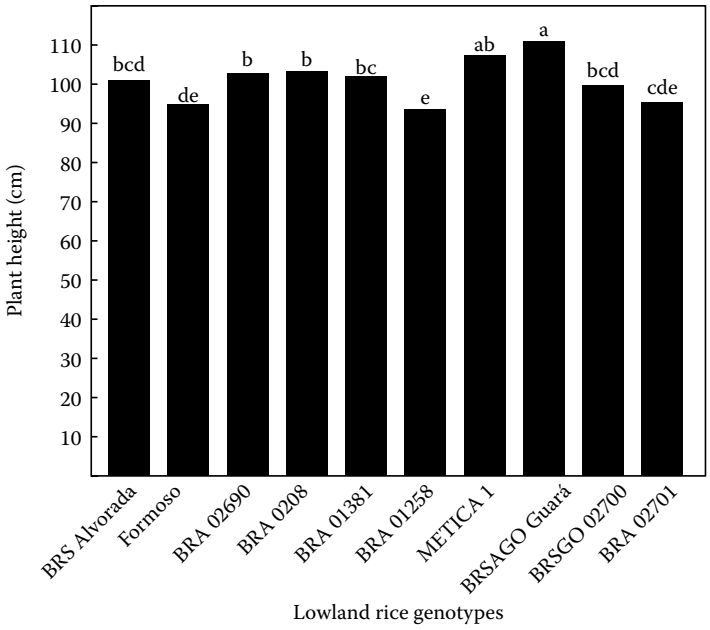

FIGURE 9.7 Plant height of 10 lowland rice genotypes.

with reduced plant height and earlier maturity, though there was no change in rice photosynthetic rate, crop growth rate, or spikelet weight (Evans et al., 1984). Despite these advantages, tall cultivars were found to compete more effectively with weeds than short cultivars. In addition, grain yields of short cultivars decreased with increasing water depth, and for deep water conditions intermediate stature (100–130 cm) have often been considered more desirable than short stature (90–110 cm) (Yoshida, 1981; Fageria et al., 2004). The plant heights of 10 contemporary lowland rice genotypes grown under Brazilian conditions are presented in Figure 9.7. In a Brazilian upland cultivar plant height increased with age, and maximum height was attained 113 days after sowing (Figure 9.8).

9.3.1.2 Root Growth

Rice seedlings initially produce a radicle (seminal root), mesocotyl root, and nodal roots (Figure 9.5). However, within a short time the rice root system is essentially composed of nodal or adventitious roots (Yoshida, 1981). Root hairs are mainly responsible for the absorption of water and nutrients, and their formation is greatly affected by the root environment. Murata and Matsushima (1975) reported that the emergence of roots takes place only when N concentration of the shoot is more than 10 g kg^{-1}. The root systems of aerobic or upland rice are larger, more vigorous, and have more root hairs than those of lowland or flooded rice. Rice roots possess large air spaces (aerynchyma) that are connected with air spaces in the culms and leaves and provide efficient conduits for oxygen to pass from shoot to root. This allows rice roots to respire and grow well under anaerobic soil conditions.

Klepper (1992) reported that crops shift from a heavy investment in root growth during seedling establishment and early vegetative growth to growth of reproductive structures during the latter part of the season. In keeping with this pattern, maximum rice root length increases linearly with plant age from tiller initiation to flowering, then remains more or less constant (Figure 9.8).

The rice plant invests up to 60% of its carbon in the root system (Nguyen et al., 1997). A root system that extends the root zone to more fully extract available soil water and mineral nutrition has the potential to increase yield under drought (Mambani and Lal, 1983; Nguyen et al., 1997). Ingram et al. (1994) and Yu et al. (1995) reported that the ability of rice to reach deep soil moisture or to penetrate compacted soil depends on developing a few thick (fibrous) and long root axes. Thick roots persist longer and produce more and larger branch roots, thereby increasing root length density and

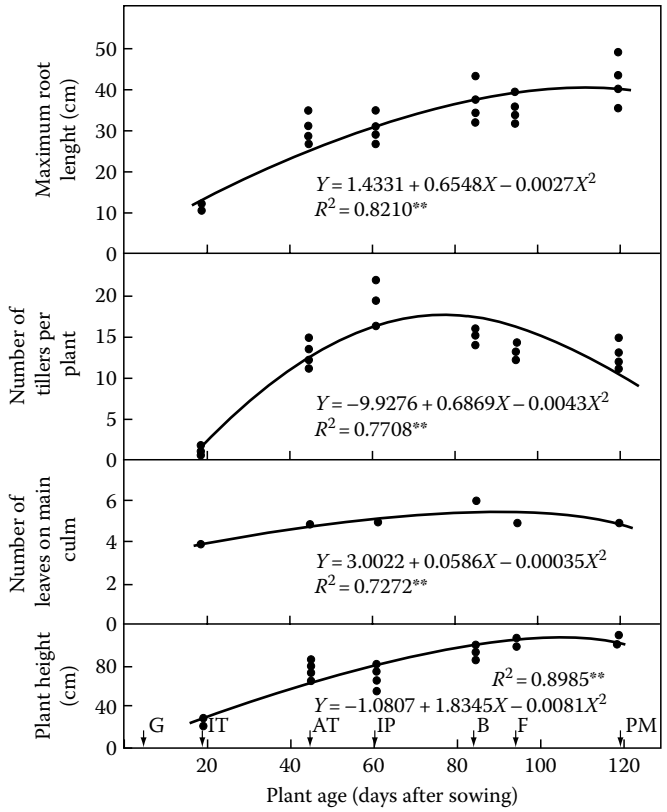

FIGURE 9.8 Relationship between plant age and morphological plant parameters. G = germination, IT = initiation of tillering, AT = active tillering, IP = initiation of panicle, B = booting, F = flowering, and PM = physiological maturity, ** significant at the 1% probability level.

water uptake capacity (Ingram et al., 1994; Nguyen et al., 1997). However, the capacity for water and nutrient uptake may limit rice productivity even in flooded soils (Ingram et al., 1994).

9.3.1.3 Tillering

Rice tiller buds are produced in the leaf axils. The carbohydrate supply required for the growth of tiller buds inside the subtending leaf sheaths is obtained from vascular bundles in the stem. After the third leaf has completely emerged, the tiller becomes autotrophic, producing its own photosynthate (Hanada, 1995). The emergence of tillers is closely linked to number of leaves on the mother stem, and tillering begins when the mother stem has four to five leaves (Murata and Matsushima, 1975). The four-to-five-leaf stage is attained 12–17 days after germination under favorable environmental conditions in the tropics. During tillering, protein synthesis is high, compared with synthesis of other organic compounds (starch, lignin, and cellulose), and the plant rapidly develops leaf area (Hayashi, 1995). In addition, tillering is influenced by environmental conditions (light, temperature, soil moisture, and N content of main stem). Cultivars with high tillering capacity can maximize their use of space and compete effectively for light and other resources. Vigorous tillering helps compensate for missing plants at low densities; however, under adequate plant densities and favorable environmental conditions, heavy tillering cultivars may produce no greater yields than cultivars with less vigorous tillering. When rice is seeded rather than transplanted, tillering capacity rarely affects grain yield because plant populations are normally high and most panicles are produced on the main culm rather than on tillers (Yoshida, 1981). Low seeding rates may, however, favor heavy tillering cultivars. Jennings et al. (1979) reported, however, that a combination of

high tillering ability and compact or nonspreading culm arrangement is desirable. Compact culms that are moderately erect allow increased solar radiation to reach tillers and produce less mutual shading per unit of land area.

Grain yield in cereals is highly dependent on the number of spikelet-bearing tillers produced by each plant (Power and Alessi, 1978; Nerson, 1980). The number of productive tillers depends on environmental conditions during tiller bud initiation and subsequent developmental stages. Numerous studies have shown that tiller appearance and abortion, or both, are affected by environmental conditions, especially nutrient deficiencies (Black and Siddoway, 1977; Power and Alessi, 1978; Masle, 1985).

Figure 9.8 illustrates that in rice tiller number first increases with age (the active tillering stage), then reaches a maximum (the maximum tiller number stage) at about 80 days. Tillers that do not produce panicles degenerate, and the number of tillers decreases until they equal the number of panicles. This period is called the ineffective tillering stage (Murayama, 1995). Nitrogen and P fertilization significantly increase tillering in rice (Fageria et al., 2003; Fageria, 2005). Murata and Matsushima (1975) reported that a shoot N concentration of more than 35 g kg^{-1} (3.5%) is necessary for active tillering, at 25 g N kg^{-1} (2.5%) tillering stops and below 15 g N kg^{-1} (1.5%) death of tillers occurs. Similarly, P concentration is correlated with tillering, and a P concentration greater than 2.5 g kg^{-1} (0.25%) in the mother stem is necessary for tillering. Data in Table 9.7 show that N significantly increased tillering in lowland rice. About 66%–96% of the variation in tillering was apparently due to N fertilization, depending on crop growth stage. Tillering increased with crop age, reached a maximum between 35 and 71 days after sowing, depending on N rate, and decreased thereafter.

The decrease in tiller number was attributed to the death of some of the last tillers as a result of their failure to compete successfully for light and nutrients (Fageria, 2007). Another explanation is that during the period of growth beginning with panicle development, competition for assimilates suppresses the heterotrophic growth of young tillers, and they senesce (Dofing and Karlsson, 1993). A correlation between grain yield and number of tillers per square meter at different growth stages is presented in Table 9.8. Tillering was related significantly with grain yield at all the growth stages; however, the highest correlation was found at initiation of panicle growth.

TABLE 9.7
Numbers of Tillers in Lowland Rice at Different N Rates during Crop Growth Cycle

	Days after Sowing					
N Rate (kg ha^{-1})	22 (IT)	35 (AT)	71 (IP)	97 (B)	112 (F)	140 (PM)
	m^{-2}					
0	506	681	652	541	499	468
30	516	749	715	547	516	495
60	574	880	772	601	571	531
90	599	759	751	597	561	522
120	632	876	812	623	573	569
150	619	862	883	660	580	592
180	557	880	903	662	588	572
210	565	819	934	666	590	581
R^2	0.82*	0.66*	0.96**	0.95**	0.91**	0.92**

Source: Fageria, N.K. and Baligar, V.C., *Commun. Soil Sci. Plant Anal*., 32, 1405, 2001.
Note: Values are averages of 3 years field trial.
IT = initiation of tillering, AT = active tillering, IP = initiation of panicle primordia, B = booting, F = flowering, PM = physiological maturity.
*,** Significant at the 5% and 1% probability levels, respectively.

TABLE 9.8
Correlation Coefficients (*r*) between Lowland Rice Grain Yield and Tiller Number at Different Growth Stages

Parameter	First Year	Second Year	Third Year
Tiller number m^{-2} at IT	0.59**	0.41*	0.23^{NS}
Tiller number m^{-2} at AT	0.69**	0.43*	0.34*
Tiller number m^{-2} at IP	0.79**	0.59**	0.68**
Tiller number m^{-2} at B	0.67**	0.52**	0.46**
Tiller number m^{-2} at F	0.70**	0.37*	0.52**
Tiller number at PM	0.77**	0.48**	0.44*

Source: Fageria, N.K. and Baligar, V.C., *Commun. Soil Sci. Plant Anal.*, 32, 1405, 2001.

Note: IT = initiation of tillering, AT = active tillering, IP = initiation of panicle, B = booting, F = flowering, PM = physiological maturity.

*,**,^{NS} Significant at the 5% and 1% probability levels and nonsignificant, respectively.

Tiller number is quantitatively inherited, but its heritability is low to intermediate, depending on cultural practices and the uniformity of the soil used for the study. Although often associated with early vigor in short-statured materials, tiller number is inherited independently of all other major characters, including plant height. Many genetic sources of heavy tillering are available in traditional tropical rice cultivars. In many crosses, erect tillers are recessive to spreading tillers, but when germplasm is selected for short culms, tiller number may increase (Jennings et al., 1979).

9.3.1.4 Shoot Dry Weight

Shoot dry weight follows a sigmoid curve with increasing plant age in upland as well as lowland rice (Figures 9.3 and 9.4). The increase in shoot weight is mainly associated with increases in the numbers and weights in leaves and culms (Fageria, 2007). The weight of rice plants consists principally of carbohydrates and proteins. Carbohydrates include cell wall constituents like cellulose and energy reserves like starch. The inorganic fraction of rice plants is generally small, though rice straw generally has up to 10% silicon (Murayama, 1995).

Dry matter loss from the vegetative tissues during the interval from flowering to maturity was 35% in upland rice, suggesting active transport of assimilates from the stems and leaves to the panicles (Figures 9.3 and 9.4) (Fageria et al., 2006; Fageria, 2007).

Increase in shoot weight is important because it is significantly associated with grain yield (Figure 9.9). Shoot weight is determined by both genotype and environmental factors. Differences have been observed in grain yield among plants or genotypes having the same amount of dry matter because genotypes differ in their utilization of photosynthates (Hayashi, 1995). Nitrogen, phosphorous, and potassium fertilization also influence shoot dry weight (Fageria et al., 2003; Fageria and Baligar, 2005). Dry matter production is more highly correlated with grain yield during the booting, flowering, and physiological maturity growth stages than earlier (Table 9.9).

Grain yield in cereals is related to biological yield and grain harvest index (Donald and Hamblin, 1976). The biological yield of a cereal crop is often considered the total yield of plant tops and is an indication of the yield of the photosynthetic capability of a crop (Yoshida, 1981). The biological yield is a function of crop growth duration and crop growth rate at successive growth stages (Tanaka and Osaki, 1983). Grain harvest index is the ratio of grain to the aboveground biological yield. The grain harvest index is controlled by the partition of photosynthates between grain and nonharvested organs like leaves and stems. Hence, economic yield is closely related to crop growth.

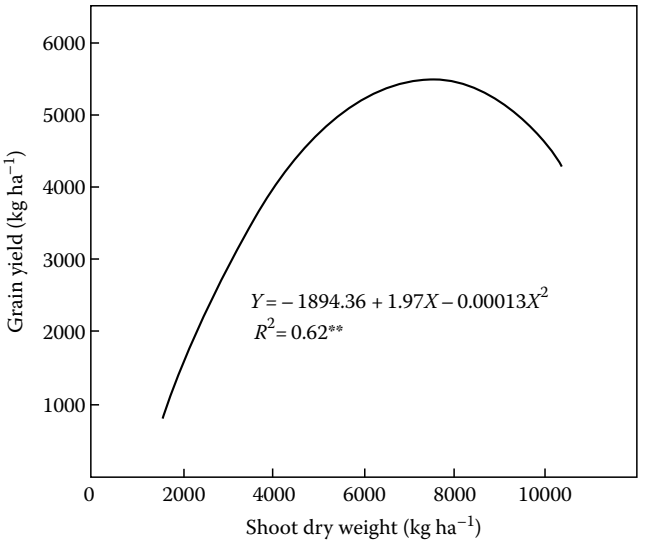

FIGURE 9.9 Relationship between shoot dry weight and grain yield of lowland rice. ** Significant at the 1% probability level.

TABLE 9.9
Correlation Coefficients (*r*) between Lowland Rice Grain Yield and Shoot Dry Matter Production during Different Growth Stages

Parameter	First Year	Second Year	Third Year
Dry matter yield at IT	0.36*	0.37*	0.29^{NS}
Dry matter yield at AT	0.71**	0.55**	0.42*
Dry matter yield at IP	0.63**	0.51**	0.63**
Dry matter yield at B	0.72**	0.81**	0.61**
Dry matter yield at F	0.81**	0.80**	0.57**
Dry matter yield at PM	0.78**	0.80**	0.53**

Source: Fageria, N.K. and Baligar, V.C., *Commun. Soil Sci. Plant Anal.*, 32, 1405, 2001.

Note: IT = initiation of tillering, AT = active tillering, IP = initiation of panicle, B = booting, F = flowering, PM = physiological maturity.

*,**,^{NS} Significant at the 0.05 and 0.01 probability levels and nonsignificant, respectively.

Grain yield can be increased either by increasing total dry matter production or by increasing grain harvest index. Some authors have speculated that a further increase in grain yield in cereals such as rice through breeding can only be accomplished with an increase in total biological yield (Rahman, 1984) and thus total straw yield. The highest grain harvest index exhibited by California lowland rice cultivars under direct seeding was 0.59 (Roberts et al., 1993).

Hasegawa (2003) has reported that for rice cultivars increased dry matter and grain harvest index contributed equally to yield increases. Peng et al. (2000) reported that yield improvement of lowland rice cultivars released by IRRI in the Philippines after 1980 was due to increases in biomass production. Similarly, Akita (1989) and Amano et al. (1996) reported that when comparisons were made among the improved semidwarf cultivars, higher yield was achieved by increasing biomass production. Song et al. (1990) and Yamauchi (1989) reported that hybrid rice cultivars had about

15% higher yield than inbred cultivars, mainly because of an increase in biomass production rather than grain harvest index. Hence, it can be concluded that the production of sufficient dry matter of shoot is important for improving grain yield of rice.

9.3.1.5 Leaf Area Index

Dry matter production in rice has been reported to be significantly related to intercepted photosynthetically active radiation (IPAR) (Kiniry et al., 2001). Crop growth depends on the amount of radiation intercepted by the crop and on the efficiency of conversion of intercepted radiation into dry matter (Sinclair and Horie, 1989). The interception of solar radiation depends on the amount of leaf area produced by the crop, which is often expressed as leaf area index (LAI). Leaf area index is an important physiological parameter that affects crop yield (Evans and Wardlaw, 1976). Light interception by the canopy is strongly influenced by LAI, and LAI is an important parameter for many crop growth models that simulate net photosynthesis and assimilate partitioning, canopy mass, and energy exchange (Fageria et al., 2006).

The LAI of a crop is the area of the leaf surface per unit area of land surface. Leaf area can be measured with a leaf area meter or by measuring the length and maximum width of each leaf and computing the area of each leaf as follows:

$$\text{Leaf area} = K \times L \times W$$

where

K is the adjustment factor
L is the leaf length
W is the leaf width

The value of K varies with the shape of the leaf, which is affected by cultivar, crop nutritional status, and leaf growth stage. Under most conditions, however, $K = 0.75$ can be used for all stages of growth except the seedling and maturity growth stages. For these two growth stages, a value of 0.67 should be used (Gomez, 1972). The LAI can be calculated as follows:

$$\text{LAI } (\text{cm}^2\ \text{m}^{-2}) = \frac{\left[A\,(\text{cm}^2) \times \text{tillers m}^{-2}\right]}{10{,}000}$$

where A is leaf area per tiller. The LAI of rice increases as crop growth advances and reaches a maximum at about heading or flowering (Yoshida, 1983). The increase in LAI is caused by an increase in tiller number, and the number and size of leaves on each tiller. In rice, the number of leaves on the main culm increases in a quadratic fashion with increasing plant age. Increasing LAI increases light interception and photosynthesis, but net canopy photosynthesis cannot increase indefinitely because of increased mutual shading of leaves.

Among various environmental factors, good N and P nutrition have marked effects on LAI by increasing the number of tillers as well as leaf size (Fageria, 2007). A N topdressing 28–44 days prior to heading markedly increased leaf area, and N topdressing 16 days before heading helped maintain leaf area and function during ripening (Oritani, 1995). Fageria (2007) reported that optimum LAI for upland rice is about 2–3 at 85–100 days after sowing. This can be compared with optimum LAI of lowland rice, which is about 4–7 (Yoshida, 1972). Yoshida (1981) reported that a LAI of 5–6 is necessary to achieve maximum crop photosynthesis during the reproductive growth stage. A LAI of 4 at heading is sufficient to produce about 5 Mg grain ha^{-1} (Yoshida, 1981). Oritani (1995) reported that maximum grain yield in lowland rice was achieved with LAI of 6–7, depending on cultivar.

The low LAI of upland rice is typically due to environmental stresses, the use of different cultivars, and lower plant populations. Rice cultivars grown under upland conditions are often subjected

to moisture stress and, in general, have fewer tillers and less leaf area than cultivars grown under lowland conditions (Chang and Vergara, 1975; Fageria et al., 1982). Lower plant density is another major factor reducing LAI in crops grown under upland conditions (Fageria et al., 2006).

9.3.2 Reproductive Growth Stage

The reproductive growth stage starts with the differentiation of panicle primordia and extends to flowering. Panicle size, or number of spikelets per panicle, is determined during this stage. Potential crop yield is primarily determined in the reproductive growth stage. The reproductive growth stage is also characterized by culm elongation, decrease in tiller number, emergence of flag leaves (the last leaf on the tiller), booting, heading, and flowering. Some aspects of panicle formation such as panicle size, compactness, and panicle exsertion are also determined during this growth stage. In the tropics the reproductive growth stage generally lasts about 30 days in rice cultivars having 130–140 days growth cycle (sowing to physiological maturity). Adverse environmental conditions such as N deficiency, drought, low solar radiation, very low or high temperatures, and blast disease can reduce panicle size and hence grain yield. A detailed description of reproductive development in rice is given by Counce et al. (2000).

9.3.3 Spikelet Filling or Ripening Growth Stage

The spikelet filling or ripening stage in rice extends from flowering to physiological maturity. It is sometimes also known as maturity growth stage. In this growth stage spikelet filling occurs and grain weight is determined. The dry weight of the caryopsis increases rapidly up to 15–20 days after flowering in the tropics and 25–30 days after flowering under temperate conditions. Some adverse environmental factors such as drought, low solar radiation, N deficiency, low or high temperatures, and panicle blast can increase spikelet sterility and, consequently, grain yield. Spikelet sterility is also genetically controlled. The spikelet filling growth stage, like the reproductive stage, lasts about 30 days growth in cultivars with a growth cycle of 130–140 days under tropical conditions (Fageria, 2007). The maximum varietal range is about 25–35 days in the tropics. The period from flowering to maturity often ranges from 45 to 60 days in temperate areas. The spikelet filling duration of japonica cultivars is often slightly longer than that of indicas (Jennings et al., 1979). Spikelet weight and spikelet sterility are the main yield components determined during this growth stage.

During the spikelet filling growth stage, LAI decreases due to leaf senescence. This is a normal process; however, it is important to maintain as many active, green leaves as possible until the linear phase of spikelet growth is completed. Ripening is subdivided into several stages, including milky, doughy, yellow-ripe, and mature, on the basis of consistency and color of the maturing grains (Murayama, 1995). During the ripening growth stage, the morphogenesis of the rice plant is already complete, and photosynthates are accumulated in the panicles in the form of starch. Mobile carbohydrates, proteins, and mineral nutrients, which are stored in leaves, stems, and roots of the plant, also move into the panicles, and these plant parts gradually senesce (Murayama, 1995).

More than 85% of rice grain is carbohydrate, primarily starch (Hayashi, 1995). The starch accumulated in rice grains originates from carbohydrates assimilated by the leaves after flowering or during grain filling, as well as from the carbohydrates stored in the shoot prior to flowering (Hayashi, 1995). Hence, to increase grain yield, it is necessary to increase the carbohydrate production during ripening and/or storage of carbohydrates prior to flowering. In most cases, the amount of carbohydrates assimilated during the ripening growth stage is much greater than that translocated from other parts of the plant (Hayashi, 1995). Osaki and Tanaka (1978) observed that the photosynthetically fixed carbon in leaves of rice was rapidly translocated to harvesting organs during ripening. Hence, a large part of carbon in the harvested organs was considered to be derived from concurrently assimilated photosynthate. Therefore, grain yield is mainly affected by the amount of carbohydrates assimilated during the ripening growth stage, especially in high-yielding, modern

cultivars (Hayashi, 1995). In addition, in high-yielding cultivars, N absorption by roots generally remains high during the spikelet filling growth stage, requiring photosynthesis and translocation of photosynthates to the roots during the ripening stage (Osaki et al., 1991b).

9.3.3.1 Spikelet Sterility

Spikelet sterility is an important factor affecting rice yields, and reducing spikelet sterility is one way to improve them. Overall, the percentage of filled spikelets is about 85% in rice, even under favorable conditions (Yoshida, 1981). Hence, the possibility exists to increase rice yields by 15% if breeding eliminates spikelet sterility. Increasing photosynthesis during grain filling could be one way to improve spikelet filling rate; however, of the 15% unfilled spikelets, about 5%–10% are unfertilized and difficult to eliminate (Yoshida, 1981). When the percentage of filled spikelets is greater than 85%, yield capacity (the sink size) can be assumed to limit yield, but when filled spikelets are less than 80%, assimilate supply (source) is yield limiting (Murata and Matsushima, 1975).

Tanaka and Matsushima (1963) reported that carbohydrates stored in the shoot at flowering increased the percentage of filled spikelets by acting as a source if concurrent photosynthesis was reduced by unfavorable conditions during grain filling. Hayashi (1995) also reported improved spikelet filling by a large amount of carbohydrate accumulated during flowering, and cultivar differences exist in the amount of carbohydrate accumulation during flowering. Furthermore, Hayashi (1995) reported that the accumulation of large amounts of carbohydrates in the shoot before flowering also reduces spikelet degeneration.

During spikelet ripening, about 70% of the N absorbed by the shoot is translocated to the spikelet for protein synthesis. Hence, reduced N absorption may induce higher spikelet sterility (Yoshida, 1981). Genotypes differ in their response to N nutrition. Data in Table 9.10 show that increasing N rate sometimes increased spikelet sterility (genotype CNAi 8860), had no effect on spikelet sterility (genotype CNAi 8569), and significantly decreased spikelet sterility (genotype BR Jaburu). Similarly, the influence of K fertilization on spikelet sterility of 10 lowland genotypes is presented in Table 9.11. Spikelet sterility was significantly influenced by K level, genotypes, and K × G

TABLE 9.10
Influence of Nitrogen on Spikelet Sterility (%) of Three Lowland Rice Genotypes

N Rate (kg ha^{-1})	CNAi 8860	CNAi 8569	BRS Jaburu
0	8.7	24.4	22.1
50	15.7	22.9	21.6
100	17.5	20.3	19.5
150	17.1	24.1	18.7
200	18.1	24.0	17.6
Average	15.4	22.0	19.9

Regression

N rate (X) vs. spikelet sterility (Y) (CNAi 8860) = $9.3543 + 0.1211X - 0.000403X^2$, $R^2 = 0.7383$**

N rate (X) vs. spikelet sterility (Y) (CNAi 8569) = $24.3312 - 0.0508X - 0.00025X^2$, $R^2 = 0.1641^{NS}$

N rate (X) vs. spikelet sterility (Y) (BRS Jaburu) = $22.3139 - 2.3933X$, $R^2 = 0.4651$**

Source: Fageria, N.K., *J. Plant Nutr.*, 30, 843, 2007.

Note: Values are averages of 2 years field trial.

**,NS Significant at the 1% probability level and nonsignificant, respectively.

TABLE 9.11
Influence of K Fertilization on Spikelet Sterility (%) of 10 Lowland Rice Genotypes

Genotype	Low K (0 mg kg^{-1} Soil)	High K (200 mg kg^{-1} Soil)
CNAi 8859	29.3b	20.3
CNAi 8860	41.0ab	20.7
BRS Fronteira	40.3ab	25.8
BRA 01435	61.5a	24.0
BRA 01436	39.1ab	24.9
BRA 01258	45.7ab	29.1
BRA 01322	26.0b	28.1
CNAi 9018	42.6ab	35.6
CNAi 9025	26.2b	26.5
BRS Alvorada	29.1b	30.9
Average	38.1	26.6
F-test		
K level (K)	*	*
Genotype (G)	*	*
K × G	*	*

Source: Fageria, N.K., *J. Plant Nutr*., 30, 843, 2007.

Note: Means in the same column followed by the same letter are not significantly different at the 5% probability level by Tukey's test.

* Significant at the 5% probability level.

interaction. Overall, spikelet sterility decreased 43% at a high K fertilizer level (200 mg K kg^{-1} soil) compared to the control treatment (0 mg K kg^{-1} soil). Genotypes also differed significantly in spikelet sterility at low fertilizer K levels. This means that spikelet sterility is influenced by environmental factors, but it is also genetically controlled, and selection for this trait is possible.

Low solar radiation during spikelet filling also increases spikelet sterility. When solar radiation is low, photosynthesis may be insufficient to produce the carbohydrates needed to support the growth of all the spikelets. As a result, the number of unfilled spikelets may increase. Low or high temperatures may also cause spikelet sterility. Spikelet sterility is induced by low temperatures during reproductive growth, a major constraint on rice production in cool climates (Shimono et al., 2005). The sensitivity of spikelet sterility to low temperatures varies during reproductive growth. The sensitivity is extremely high at the young microspore stage, which is a stage of active cell division, and decreases as the plant develops beyond this stage (Hayase et al., 1969).

Air temperatures below 20°C may cause a high percentage of sterility if they persist for a few days at booting or heading (Yoshida, 1981). Similarly high temperatures (>35°C) at anthesis or flowering may cause high spikelet sterility. Large disease or insect pressure during the reproductive or spikelet filling stage may also increase spikelet sterility. Besides breeding cultivars for tolerance of low-temperature stress, management practices such as changing planting date, water management, and fertilization have been recommended to Japanese farmers in an effort to prevent yield losses caused by spikelet sterility induced by low temperatures (Wada, 1992; Shimono et al., 2005). Satake et al. (1988) reported that water management is the most important practice to prevent yield losses due to unusually low temperatures, since deep flooding can help maintain a warmer microclimate than shallower waters.

Yamamoto et al. (1991) reported that increasing the number of spikelets per panicle causes overproduction of spikelets on secondary branches and sterility of these spikelets than that of spikelets

TABLE 9.12
Spikelet Weight of 10 Lowland Rice Genotypes Grown in Brazilian Inceptisol

Genotype	1000 Spikelet Weight (g)
BRS Jaçana	25.3bcd
CNAi 8860	26.5abc
BRS Fronteira	27.0ab
CNAi 8879	27.4a
CNAi 8880	26.6abc
CNAi 8886	26.7abc
CNAi 8885	24.7d
CNAi 8569	26.0abcd
BRSGO Guará	25.0cd
BRS Alvorada	26.2abcd
BRS Jaburu	26.5abc
BRS Bigua	26.2abcd
Average	26.2

Source: Fageria, N.K., *J. Plant Nutr*., 30, 843, 2007.
Note: Means in the same column followed by the same letter are not significantly different at the 5% probability level by Tukey's test.

on primary branches. Kato (1997) reported that it is possible to develop cultivars with higher filled-grain percentages by increasing the number of primary branches and suppressing the number of spikelets on secondary branches.

9.3.4 Spikelet Weight

Spikelet weight in rice is generally expressed in terms of 1000 grain weight in grams. Spikelet size is rigidly controlled by hull size and, under most conditions, the 1000 spikelet weight of rice is a very stable varietal character. Data in Table 9.12 show spikelet weight of 10 lowland rice genotypes. It varied from 24.7 to 27.4 g, with average value of 26.2 g. Hence, there was a difference of only about 11% in spikelet weight between lowest and highest weight-producing genotypes.

9.4 YIELD AND POTENTIAL YIELD

Yield is defined as the amount of specific substance produced (e.g., grain, straw, total dry matter) per unit area (Soil Science Society of America, 1997). *Grain yield* refers to the weight of cleaned and dried grains harvested from a unit area. For rice, grain yield is usually expressed either in kilograms per hectare (kg ha^{-1}) or in metric tons per hectare (Mg ha^{-1}) at 13% or 14% moisture. The yield of a crop is determined by management practices, including crop genotype, water management, and control of insects, diseases, and weeds.

Potential yield is defined as an estimate of the upper limit of yield that can be obtained from a crop (Fageria, 1992). *Genetic yield potential* is defined as a yield of adapted lines in a favorable environment in the absence of agronomic constraints (Reynolds et al., 1999). Evans and Fischer (1999) defined potential yield as the maximum yield that can be reached by a crop or genotype

in a given environment. These authors further reported that the term potential yield is often used synonymously with yield potential. However, Evans and Fischer (1999) defined yield potential as the yield of a cultivar when grown in environments to which it is adapted, with nutrients and water non-limiting and with pests, diseases, and weeds, lodging, and other stresses effectively controlled. Evans and Fischer (1999) further reported that there is no evidence that a ceiling on yield potential has been reached, but should this occur, average yields could still continue to rise as crop management improves and as plant breeders continue to improve resistance to pests, diseases, and environmental stresses. Hybrid rice between indicas increased yield potential by about 9% under the tropical conditions (Peng et al., 1999). The higher yield potential of indica/indica hybrids compared with indica inbred cultivars was attributed to the greater biomass production rather than to increased harvest index. These authors also reported that breeding for new plant types has not yet improved rice yield potential due to poor grain filling and low biomass production. However, work is in progress at the IRRI to remove this yield barrier and increase yield potential of rice.

Potential yield is, in a way, the most optimistic estimate of crop yield that is based on present knowledge and available biological material, under ideal management, in an optimum physical environment. Rasmusson and Gengenbach (1984) reported that the genetic potential of a plant or genotype is manifested through the interrelationships among genes, enzymes, and plant growth. The combined effect of many genes, through their control of enzymes, results in physiological traits contributing to plant growth, development, and yield (Rasmusson and Gengenbach, 1984).

Yield potential is generally determined by calculating photosynthesis during a spikelet-filling period (Murata and Matsushima, 1975). For rice growing in an environment where the daily amount of solar radiation received is 16.7 MJ m^{-2}, assuming an efficiency of 26% in photosynthesis, the net carbohydrate production in a 40 day spikelet-filling period was calculated to be 16.4 Mg ha^{-1} (Austin, 1980; Fageria, 1992). Over the years, rice yields have increased due to advances in breeding and crop management. The new plant type lines are characterized by fewer tillers and a greater density of spikelets (Kobata et al., 2006). New rice cultivars have been released that possess yield potential >10 Mg ha^{-1} (Ottis and Talbert, 2005; Kobata et al., 2006).

World average rice yield is about 3.8 Mg ha^{-1}. However, in experiments conducted by the author in the central part of Brazil, a grain yield of 6–7 Mg ha^{-1} of lowland rice is very common (Fageria and Baligar, 2001; Fageria and Prabhu, 2004). Even a grain yield of 10 Mg ha^{-1} of lowland rice was obtained in a field experiment conducted in the central part of Brazil (Fageria and Prabhu, 2004). Similarly, in the State of Mato Grosso, Brazil, upland rice yields measured in the farmers' field varied from 1 to 7.8 Mg ha^{-1} with an average value of 3.6 Mg ha^{-1} (Fageria and Breseghello, 2004). Similarly, Peng and Cassman (1998) reported lowland rice yield of 9 Mg ha^{-1} at the IRRI, Los Bânos, Philippines. This indicates that there is a large gap between yield obtained in farmers' fields and at experimental sites. This gap can be reduced significantly if appropriate technologies are adopted and the socioeconomical conditions of rice farmers improve.

9.5 YIELD COMPONENT ANALYSIS

Rice yield is determined by yield components: the number of panicles, spikelets per panicle, weight of 1000 spikelets, and spikelet sterility or filled spikelet percentage (Fageria, 2007). Therefore, it is very important to understand the management practices that influence yield components and consequently grain yield. Fageria and Baligar (2001) reported that the application of N in adequate amounts accounted for about 91% variation in panicles per square meter, about 75% of the variation in spikelet sterility, and about 73% of the variation in 1000 grain weight. As discussed earlier, the number of panicles is determined during the vegetative growth stage, spikelet per panicle during the reproductive growth stage, and spikelet weight and sterility during spikelet filling or reproductive growth stage. Hence, adequate N supply throughout

TABLE 9.13
Relationship between Grain Yields (*Y*) and Plant Growth and Yield Components (*X*)

Grain Yield vs. Growth and Yield Components	Regression Equation	R^2
Shoot dry weight vs. grain yield	$Y = -127.4503 + 3.5281X - 0.0158X^2$	0.3111**
Number of panicles vs. grain yield	$Y = -26.8657 + 2.3909X$	0.5169**
1000 grain wt. vs. grain yield	$Y = -83.7798 + 5.9842X$	0.3701**
Spikelet sterility vs. grain yield	$Y = 122.5637 - 2.5863X + 0.0158X^2$	0.4331**

Source: Fageria, N.K., *J. Plant Nutr*., 30, 843, 2007.
** Significant at the 1% probability level.

the growth cycle of rice plant is one of the main strategies to increase grain yield. Rice yield can be expressed in the form of the following equation:

$$\text{Grain yield (Mg ha}^{-1}) = \text{Number of panicles m}^{-2} \times \text{Spikelets panicle}^{-1} \times \% \text{ filled spikelets} \times 1000 \text{ spikelet weight(g)} \times 10^{-5}$$

Among these yield components, panicles or spikelets per unit area is usually the most variable yield component (Fageria, 2007). The number of panicles per unit area is determined during the period up to about 10 days after maximum tiller number is reached (Murata and Matsushima, 1975). The importance of yield components in determining grain yield is generally in the order of: number of panicles > spikelet sterility > 1000 grain weight (Table 9.13). Gravois and Helms (1992) reported that optimum rice yield could not be attained without optimum panicle density and uniform panicle maturity. Similarly, Ottis and Talbert (2005) reported a high correlation ($R^2 > 0.85$) between yield and panicle density. The most important factor for the determination of spikelet number during reproductive growth stage is the amount of N absorbed, although photosynthesis also contributes to the determination of spikelet number (Ishii, 1995). Similarly, the specific absorption rate of N per unit root dry weight during grain filling stage is the most important factor for achieving high rice productivity (Osaki et al., 1995).

The grain yield in rice is determined by carbohydrates accumulated in the plant before heading and after heading. Carbohydrates produced before heading mainly accumulate in the leaf sheath and stem and are translocated to the panicles during grain filling. Murata and Matsushima (1975) reported that the contribution of the carbohydrates produced before heading to the final grain yield appeared to be in the range of 20%–40%. Hence, about 70% of the grain yield is produced from the carbohydrates produced after heading, and photosynthesis after heading is vital for yield sustainability. The major photosynthetic organ contributing to grain yield after heading is the flag leaf, although the contribution of the second through fourth leaves is also fairly large (Ishii, 1995).

9.6 GRAIN HARVEST INDEX

Grain harvest index (GHI) is the ratio of grain yield to total biological yield. This index is calculated with the help of equation: GHI = grain yield/(grain + straw yield) (Fageria and Baligar, 2005). Although GHI is a ratio, it is sometimes also expressed in percentages. Snyder and Carlson (1984) reviewed GHI for selected annual crops and noted variations from 0.40 to 0.47 for wheat, 0.23–0.50 for rice, 0.20–0.47 for bunch-type peanut (*Arachis hypogaea* L.), and 0.39–0.58 for dry bean. The GHI values of modern crop cultivars are commonly higher than traditional cultivars for major field crops (Ludlow and Muchow, 1990). Mae (1997) reported that the GHI of traditional rice cultivars

is about 0.30 and 0.50 for improved, semidwarf cultivars. Rice GHI values varied greatly among cultivars, locations, seasons, and ecosystems, and ranged from 0.35 to 0.62, indicating the importance of this variable for yield simulation (Kiniry et al., 2001). Amano et al. (1996) reported harvest index of 0.67 with japonica F_1 hybrid rice in Yunnan Province, South China. Osaki et al. (1991a) reported a GHI of 0.39 for standard old cultivar and 0.47 for modern, high-yielding cultivar in Japan. The highest harvest index exhibited by California cultivars under direct seeding was 0.59 (Roberts et al., 1993), which is consistent with the maximum harvest indices of 0.60–0.65 reported for high-yielding semidwarf cultivars in transplanted rice (Rahman, 1984). This 0.60–0.65 range is viewed as a theoretical maximum because of the structural difficulty of supporting more than 65% of the total biological yield as grain on less than 35% of the biological yield as straw (Roberts et al., 1993).

9.7 NUTRIENT REQUIREMENTS

Nutrient requirements for upland and lowland rice are different due to differences in yield levels and growing conditions. In lowland rice, environmental conditions are mostly stable and favorable for plant growth, and high fertilizer application can ensure high yields. However, in the case of upland rice, inadequate water, particularly around flowering, often reduces yield significantly (Fageria, 1980). Under such circumstances, there is little or no difference in yield between well-fertilized and underfertilized crops. In fact, the higher leaf area and rate of water use of well-fertilized crops can render them more susceptible to the stress of prolonged drought (>10 days) around flowering (Fageria, 1980). Therefore, fertilizer recommendations for upland rice should take into account the risk of drought. Another factor that should be taken into consideration is the incidence of blast disease in upland rice. If precautions are not taken to control this disease, panicle neck blast can cause total crop failure. Excess N application sometimes increases blast infection in upland rice (Faria et al., 1982). Since environmental conditions and yield levels are different for upland and lowland rice, nutrient requirements for these two rice cultures are discussed separately in this section.

9.7.1 Upland Rice

Rice grown in rainfed, naturally drained soils, without surface water accumulation, normally without phreatic water supply, and normally not bunded, is called upland rice (Garrity, 1984). About half of the world's 135 million ha of rice land is rainfed, and, of this, 19.1 million ha is dryland. As such, dryland accounts for 14% of the total rice area and 29% of the rainfed area (Garrity, 1984). Most upland rice production occurs in South America, Asia, and Africa (Gupta and O'Toole, 1986). Soil fertility is one of the major constraints in upland rice production. Soil acidity, low CEC, and high P fixation capacity are the major soil chemical properties affecting upland rice production. In South America, for example, the Cerrado region is situated in the central part of Brazil, and its total area is about 200×10^6 ha. At present, 3% of the Cerrado is under cultivation, and it is estimated that at least 50×10^6 ha could be used for crop production (Goedert, 1983). Low soil fertility is the main constraint on crop production in Cerrado soils. For upland rice production in Brazil, P is the most important yield-limiting nutrient (Fageria and Baligar, 1997; Fageria, 2001a). This is due to the low inherent P level of the soil (<2 mg kg^{-1}) and high P immobilization capacities (Fageria and Barbosa Filho, 1987). Deficiencies of N, K, Ca, Mg, and Zn have also been reported (Barbosa Filho and Fageria, 1980; Goedert, 1983; Fageria, 2001a, 2009).

9.7.2 Nutrient Concentration and Uptake

Plant tissue tests are used to identify nutritional disorders in crop plants. Nutrient concentration is content per unit dry weight, and uptake or accumulation is concentration × dry matter. Plant tissue testing is the most expensive technique used to identify nutritional deficiencies. To accurately interpret plant tissue testing results, it is necessary to have plant analysis results for each crop under different agroecological conditions. Critical plant nutrient levels vary with crop species, plant age, and plant part

TABLE 9.14
Macro- and Micronutrient Concentrations in the Top of Upland Rice during Crop Growth Cycle

	Days after Sowing					
Nutrient	**19**	**44**	**68**	**88**	**97**	**126**
N (g kg^{-1})	47.7	30.2	18.7	16.2	16.0	8.7
P (g kg^{-1})	3.6	1.7	1.1	1.1	0.8	0.5
K (g kg^{-1})	33.0	31.2	27.5	23.5	25.0	23.5
Ca (g kg^{-1})	3.3	3.8	3.1	2.6	2.8	3.6
Mg (g kg^{-1})	2.7	2.7	2.4	2.1	2.2	2.2
Zn (mg kg^{-1})	40	29	21	22	24	26
Cu (mg kg^{-1})	22	12	8	7	6	5
Mn (mg kg^{-1})	250	217	145	150	147	205
Fe (mg kg^{-1})	1325	300	157	82	57	104
B (mg kg^{-1})	10	9	9	9	7	8

Source: Fageria, N.K., Evaluation nutritional status of rice, in *Technology of Upland Rice*, Breseghello, F. and Stone, L.F. (eds.), Embrapa Arroz e Feijão, Santo Antônio de Goias, Brazil, 59–66, 1998.

analyzed. Many factors, including soil, climate, plant and their interactions affect absorption of nutrients by growing plants. However, the concentrations of essential nutrients are maintained within rather narrow limits in plant tissues. Such consistency is thought to arise from the operation of delicate feedback systems, which enable plants to respond in a homeostatic fashion to environmental fluctuations (Fageria and Baligar, 2005). Hence, it can be concluded that plant analysis results are more stable than soil testing results, and plant analysis results for a specific crop varies little from one location to another.

Concentrations of macro- and micronutrients in upland rice tops during the crop growth cycle are presented in Table 9.14. The concentrations of almost all nutrients in the shoot decrease with increasing plant age. This is expected because with increasing plant age, more carbon-rich, nutrient-poor structural materials like cellulose and lignin accumulate, diluting the concentration of accumulated nutrients. Among macronutrients, the concentration of K was higher than other nutrients at all growth stages, except at 19 days of growth. The accumulation of macro- and micronutrients in straw and grain of upland rice are presented in Table 9.15. On a whole-plant basis, rice cultivars accumulated more K than N and more N than P. Grains accumulated more N and P than straw, but K accumulation was higher in straw than in grain. Among micronutrients, the accumulation order was: Mn > Fe > Zn > Cu > B. To produce 1 metric ton of grain, upland rice accumulated 28 kg N, 3 kg P, 45 kg K, 6 kg Ca, and 4 kg Mg in grain and straw. Among micronutrients, the accumulation was 65 g Zn, 20 g Cu, 169 g Fe, 351 g Mn, and 18 g B (Table 9.15).

9.7.3 Fertilizer Recommendations

Upland rice, like other annual crops, requires large amount of N, P, and K fertilization for maximum economic yields. On Oxisols and Ultisols, where most of the upland rice is grown in Brazil, a fertilizer N rate of 90–120 kg ha^{-1} is recommended. Half of this rate is applied at sowing and the remainder at the active tillering growth stage (about 45 days after sowing). The source of N is also important for upland rice. Ammonium sulfate and urea are the main sources of fertilizer N for annual crop production in the developing countries. A study by Fageria and Moreira (2010) compared these two sources on upland rice grain yield, shoot dry weight, and panicle number. Grain yield, shoot dry weight, and panicle number were significantly influenced by N sources and N rates (Figures 9.10 through 9.12). At higher and lower N rates ammonium sulfate produced higher grain

TABLE 9.15
Uptake of Macro- And Micronutrients by Upland Rice Grown on Brazilian Oxisol

Nutrient	Straw	Grain	Total	Required to Produce Metric Tons of Grain
N (g kg^{-1})	56	70	126	28
P (g kg^{-1})	3	9	12	3
K (g kg^{-1})	150	56	206	45
Ca (g kg^{-1})	23	4	27	6
Mg (g kg^{-1})	12	5	19	4
Zn (mg kg^{-1})	161	138	299	65
Cu (mg kg^{-1})	35	57	92	20
Fe (mg kg^{-1})	654	117	771	169
Mn (mg kg^{-1})	1319	284	1603	351
B (mg kg^{-1})	53	30	83	18

Source: Adapted from Fageria, N.K. and Stone, L.F., Micronutrient deficiency problems in South America, in *Micronutrient Deficiencies in Global Crop Production*, Alloway, B.J. (ed.), Springer, New York, 247–268, 2008.

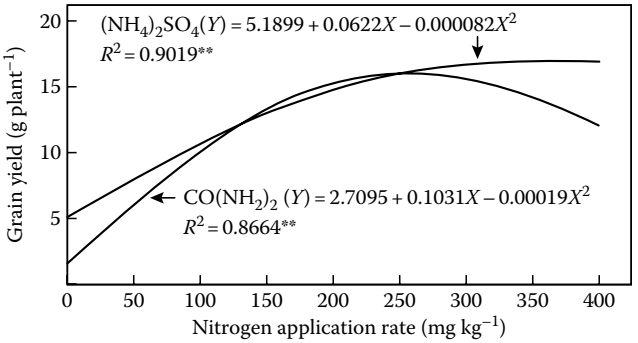

FIGURE 9.10 Relationship between nitrogen application rate by ammonium sulfate and urea and grain yield of upland rice, ** significant at the 1% probability level. (From Fageria, N.K. and Moreira, A., *J. Plant Nutr.*, 32, 2010, in press.)

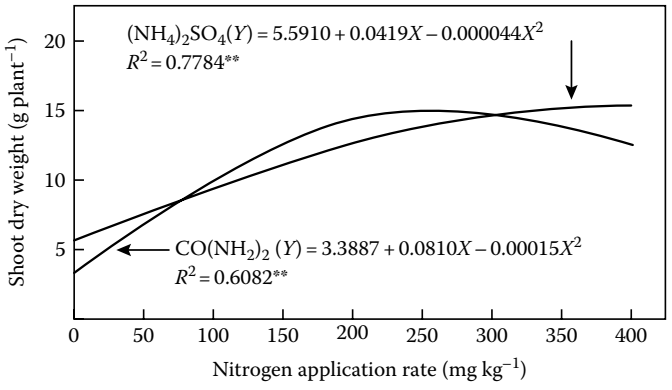

FIGURE 9.11 Relationship between nitrogen application rate by ammonium sulfate and urea and shoot dry weight of upland rice, ** significant at the 1% probability level. (From Fageria, N.K. and Moreira, A., *J. Plant Nutr.*, 32, 2010, in press.)

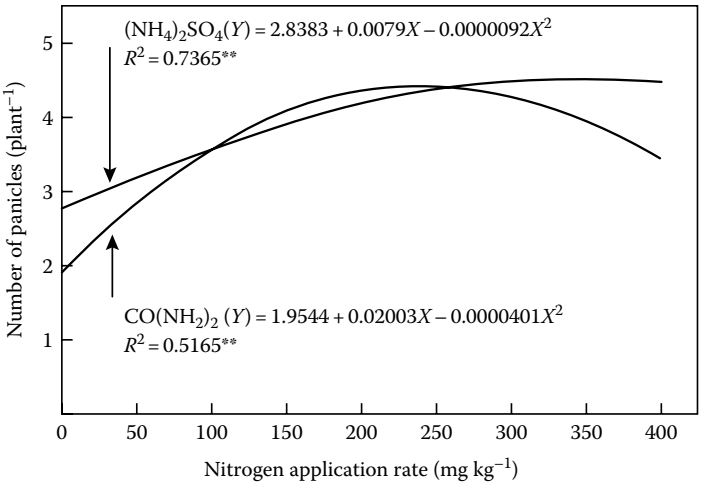

FIGURE 9.12 Relationship between nitrogen application rate by ammonium sulfate and urea and number of panicles of upland rice, ** significant at the 1% probability level. (From Fageria, N.K. and Moreira, A., *J. Plant Nutr.*, 32, 2010, in press.)

yield, shoot dry matter, and panicle number than urea. At the intermediate N rate (125–275 mg N kg^{-1}) urea was slightly better than ammonium sulfate for grain production.

Upland rice in Brazilian Oxisols and Ultisols generally responds to P fertilization when P level in the soil is less than 5 mg kg^{-1} by the Mehlich-1 extracting solution. A P fertilizer rate of 100–120 kg ha^{-1} (P_2O_5) is recommended when P level is below 3 mg P kg^{-1} of soil. When P level is higher than 3 mg kg^{-1}, the P fertilizer rate can be lowered to 60–80 kg P_2O_5 ha^{-1}, preferably applied in the furrow at sowing. The K requirement of upland rice is also high due to high land requirements and low soil reserves of these essential nutrients (Fageria, 2009). The rate recommended is 80–120 kg K ha^{-1}, depending on initial K level of the soil. In addition, Zn deficiency is frequently observed in upland rice grown on Brazilian Oxisols and Ultisols. Zinc fertilizer at the rate of 5 kg Zn ha^{-1} is sufficient to produce maximum economic yield.

9.8 LOWLAND RICE

Lowland rice is grown in submerged or waterlogged soils. The most important differences between submerged soils and upland soils are caused by the supply of O_2 to the soils. Under submerged conditions, an adequate supply of O_2 is ordinarily restricted to the surface layer of the soil and close proximity of roots. Except for these sites, the depletion of O_2 significantly affects microbial metabolism and soil N transformations. Patrick (1982) summarized the characteristic features of anaerobic bacterial degradation of organic matter in submerged soils. He indicated that the accumulation rates of inorganic N (ammonium) under anaerobic conditions are faster than would be expected from the C/N ratio of organic matter and slow microbial decomposition due to the low requirement of N in anaerobic metabolism (Nishio et al., 1994).

Ponnamperuma (1972) has divided the submerged soils into three groups: (1) waterlogged (gley) soils, (2) marsh soils, and (3) paddy soils. He described waterlogged soils as those saturated with water for a sufficiently long time to give the soil the distinctive gley horizons resulting from oxidation–reduction processes. Normally, in such soils, there are three distinct horizons. A partially oxidized A horizon is high in organic matter due to reduced rates of oxidation in intermittently saturated soils. The second horizon is a mottled zone in which oxidation and reduction alternate, and iron and manganese are deposited as rusty mottles or streaks if the diffusion of oxygen into the soil aggregate is slow. The third horizon is a permanently reduced zone which is bluish green due to the presence of ferrous compounds. Waterlogged soils occur in almost any

climatic zone from the tundra to the desert or humid tropics. Saturation with water may be due to impermeability of the soil material, the presence of an impervious layer, or a high water table (Ponnamperuma, 1972).

Marsh soils may be defined as soils that are more or less permanently saturated or submerged. The important characteristics of these soils are the accumulation of plant residues in the surface horizon and the presence of a permanently reduced G horizon below it. The third group of submerged soils consists of paddy soils that are managed in a special way for flooded rice cultivation. Land for flooded rice cultivation is leveled, bunded, provided with a surface drainage system, puddled (plowing and harrowing of saturated soil to reduce deep percolation of irrigation water), flooded to maintain 10–15 cm of standing water during most of the crop growth period, and drained at harvest. Because of the submergence of these soils, certain electrochemical changes take place in them which affect nutrient availability and growth. It is important to give a brief discussion of the electrochemical changes to better understand mineral nutrition of lowland rice.

9.8.1 Electrochemical Changes in Submerged Soils

Lowland rice rhizosphere environment is different than that of upland rice. Flooding the soil drastically reduces soil oxygen content and causes several electrochemical changes which influence rice growth and yield. Detailed discussions of these changes are given by Ponnamperuma (1972, 1978), Patrick and Mikkelsen (1971), De Datta (1981), Fageria (1984a), Barbosa Filho (1987), and Fageria et al. (2003). They are

1. Depletion of molecular oxygen
2. Decrease in redox potential (Eh)
3. Increase in pH of acid soils and decrease in pH of alkaline soils
4. Increase in specific conductance and ionic strength of the soil solution
5. Reduction of Fe^{3+} to Fe^{2+} and Mn^{4+} to Mn^{2+}
6. Reduction of NO_3^- and NO_2^- to N_2 and N_2O
7. Reduction of SO_4^{2-} to S^{2-}
8. Increase in supply and availability of N, P, K, Ca, Mg, Fe, Mn, Mo, and Si
9. Decrease in supply and availability of Zn, Cu, and S
10. Liberation of CO_2, CH_4, organic acids, and H_2S

The change in soil pH to near neutrality affects growth by influencing the following processes (Ponnamperuma, 1978; De Datta and Mikkelsen, 1985):

1. Adverse effects of low or high pH per se are minimized.
2. Availability of many nutrients is increased.
3. Excess Al^{3+} and Mn^{4+} in acid soils are rendered harmless.
4. Iron toxicity in acid soils is reduced.
5. Organic acids decompose and are not highly ionized.

9.8.2 Management of Nitrogen in Lowland Rice

Lowland rice, also known as flooded and paddy rice, is responsible for about 76% of total rice production at the world level (Fageria et al., 2003). In lowland rice culture, two basic methods of sowing are adopted. These methods are transplanting and direct seeding. In recent years, direct seeding is becoming more common where there is labor shortage and mechanization is practiced. Nitrogen is one of the nutrients that limits rice yields in all rice growing soils of the world (Yoshida, 1981; Fageria et al., 2003, 2007; Santos et al., 2003; Fageria and Baligar, 2005). Nitrogen application significantly increased lowland rice yield in Brazil (Fageria and Baligar, 1996, 2001;

Fageria et al., 2003, 2007), China (Yang, 1987), India (De Datta, 1981, 1986, 1987), Philippines (Dobermann et al., 2000), Japan (Yoshida, 1981), Africa (Gaudin and Dupuy, 1999), and the United States (Wilson et al., 2001). Nitrogen is essential to the growth of the rice plant, and about 75% of leaf N is associated with chloroplasts, which are essential to dry matter production through photosynthesis (Fageria, 2009). Rice plants require N during vegetative growth to produce leaves and tillers. During the reproductive stage, rice needs N to produce adequate grain numbers, and during grain filling N is required to produce grain protein and grain weight (Fageria, 2007). Dobermann and Fairhurst (2000) reported that N increases plant height, panicle number, leaf size, spikelet number, and number of filled spikelets, ultimately determining the yield potential of a rice plant. Leaching, volatilization, denitrification, and surface runoff are principal pathways of N loss in lowland rice (Fageria and Baligar, 2005). Hence, lowland rice provides unique and challenging environment for N management. Crop response to applied N and N use efficiency are important criteria for evaluating crop N requirements and testing the efficiency of N management practices for maximum economic yield (Fageria et al., 2003).

Ladha and Reddy (2003) compared lowland rice grain yields and plant N requirements as they have increased through the years. Grain yields before the first green revolution were approximately 3 Mg ha^{-1}, with the rice crop requiring about 60 kg N ha^{-1}. During the first green revolution, grain yields reached 8 Mg ha^{-1}, with the rice crop requiring 160 kg N ha^{-1}. The second green revolution or evergreen revolution is expected to produce grain yield of 12 Mg ha^{-1} and require 240 kg N ha^{-1} (Samonte et al., 2006). Nitrogen is one of the most difficult plant nutrients to manage because of the large number of potential transformation pathways. A normal recovery of fertilizer nitrogen applied to wetland rice crop is seldom more than 30%–40% and, even with the best agronomic practices, rarely exceeds 60%–68% (De Datta et al., 1983). The low efficiency of fertilizer N in lowland rice is related to ammonia volatilization, denitrification, leaching, ammonium fixation, immobilization, and runoff (Savant and De Datta, 1982). Recent nitrogen transformation studies indicate that NH_3 volatilization in lowland rice soils is an important loss mechanism, causing a 5%–47% loss of applied fertilizer under field conditions. De Datta (1987) estimated that denitrification losses are between 28% and 33%.

The biological oxidation of NH_4^+-N to NO_3^--N (nitrification) results in the conversion of the relatively immobile NH_4^+ cation into the more mobile anion (NO_3^-) form, which is susceptible to leaching and denitrification. Submerged soils are an ideal environment for denitrification, since the thin oxidized surface layer promotes nitrification and a deeper reduced zone favors denitrification (Mikkelsen, 1987). The N use efficiency of lowland rice can be improved by adopting appropriate crop management practices like (1) use of adequate rate, (2) improved timing of N application, (3) improved N sources and methods of application, (4) planting N efficient genotypes, and (5) better water management and control of diseases and weeds.

9.8.2.1 Adequate Rate

Nitrogen is a dynamic and mobile nutrient in soil-plant systems. A major part of the N in the soil is present in organic forms. The mineralization of organic N depends on microbial activity, which is influenced by environmental factors. Further, there are many sources of addition and loss pathways of N in the soil-plant system, which complicate its use by plants. Hence, N concentration changes in the rhizosphere with time and space. Therefore, for lowland rice soil analysis is not an effective means of making fertilizer N recommendations, as it is in the case of immobile nutrients like P and K. Dobermann and Fairhurst (2000) reported that no suitable soil test method has been established and implemented for determining the N supply capacity for lowland soils used to produce rice. Hence, a crop response curve showing yield versus fertilizer N rates is the most efficient and effective method of defining N requirement of lowland rice (Fageria and Baligar, 2005). Figure 9.13 shows the response of lowland rice to applied N in a Brazilian Inceptisol. There was a significant quadratic increase in grain yield with increasing N rate in the range of 0–200 kg ha^{-1}. The N rate to obtain 90% of maximum yield, which is considered as an economic rate, was obtained

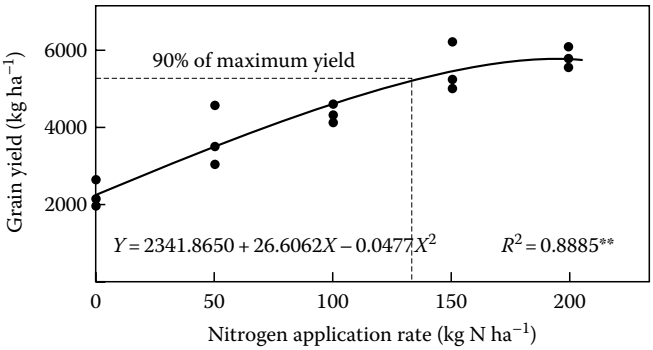

FIGURE 9.13 Relationship between nitrogen application rate and lowland rice grain yield, ** significant at the 1% probability level. (From Fageria, N.K. et al., *J. Plant Nutr.*, 31, 1121, 2008a.)

at the N rate of about 135 kg ha^{-1}. Fageria and Baligar (2001) also reported a significant quadratic response of lowland rice yields in a Brazilian Inceptisol when fertilizer N was applied in the range of 0–210 kg ha^{-1}.

Fageria and Baligar (2001) reported that the maximum economic yield of lowland rice cultivated for 3 consecutive years in the same area was obtained with the application of 90 kg N ha^{-1}. Dobermann et al. (2000) reported that irrigated rice cultivar IR72 yield increased significantly up to 150 kg N ha^{-1} at the IRRI in the Philippines. Tem Berge and Riethoven (1997) reported that in China adequate rate of N for lowland rice cultivars of medium growth cycle varied from 100 to 150 kg ha^{-1}. The maximum yields of modern lowland rice cultivars in the State of Rio Grande do Sul of Brazil were obtained with N rates of 114–126 kg ha^{-1}, depending on the region and type of soil (Vahl, 1999). When N is applied at recommended rates, N use efficiency is higher and N losses are minimized. When N is applied at higher rates than those necessary for maximum economic yield, N accumulates in the soil profile and losses are higher.

9.8.2.2 Timing of Nitrogen Application

Nitrogen is lost from soil-plant system via volatilization, leaching, denitrification, and runoff (Fageria and Baligar, 2005). More N is available for loss during the growing season if N is applied only once during the cropping season, and splitting the N fertilizer applications can reduce losses and improve N use efficiency. For lowland rice under Brazilian conditions, applying half of the N in a band at sowing and the remainder 6–7 weeks later should increase both N fertilizer use efficiency and N uptake by minimizing leaching opportunity time and better timing N application to N uptake (Fageria and Baligar, 1999a). Fageria and Baligar (1999a) reported that the agronomic efficiency of N in lowland rice was higher when N was applied in three split applications (one-third at sowing + one-third at active tillering + one-third at panicle initiation), compared with applying all the fertilizer N at sowing. A similar study conducted by Fageria and Prabhu (2004) on the Brazilian Inceptisol showed that fertilizer N split into two or three equal doses produced higher lowland rice grain yields than a single application at sowing (Figure 9.14). The beneficial effects of split application of N during early vegetative growth stage have been reported in Mississippi by Walker et al. (2006). The split applications of N are most beneficial in sandy soils and high rainfall areas.

9.8.3 Source and Method

Nitrogen sources and the methods of application significantly influence N uptake efficiency in crop plants. Important considerations in selecting a source of N include availability, economics, convenience in storage and handling, and effectiveness of the carrier. Generally, urea and ammonium sulfate are the principal sources of fertilizer N. However, a number of fertilizers containing N are

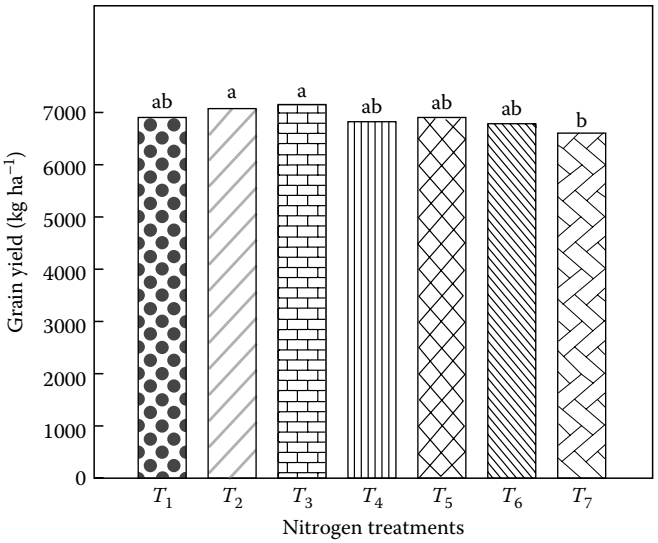

FIGURE 9.14 Grain yield of lowland rice as influenced by N timing treatments. T_1 = all the N applied at sowing, T_2 = 1/3 N applied at sowing + 1/3 N applied at active tillering + 1/3 N applied at the initiation of panicle primordia, T_3 = 1/2 N applied at sowing + 1/2 N applied at active tillering, T_4 = 1/2 N applied at sowing + 1/2 N applied at the initiation of panicle primordia, T_5 = 2/3 N applied at sowing + 1/3 N applied at active tillering, T_6 = 2/3 N applied at sowing + 1/3 N applied at initiation of primordia floral, and T_7 = 1/3 N applied at sowing + 2/3 N applied at 20 days after sowing. (Adapted from Fageria, N.K. and Prabhu, A.S., *Pesq. Agropec Bras*., 39, 123, 2004.)

available in the market (Fageria and Baligar, 2005). In the United States, anhydrous ammonia (NH_3) is an important source of fertilizer N. At atmospheric pressure NH_3 is a gas, but it is transported and handled as a pressurized liquid. It is injected into the soil to prevent loss through volatilization. The NH_3 protonates to form NH_4^+ in the soil, which is stable. The major advantages of anhydrous ammonia are its high N analysis (82% N) and low cost of transportation and handling. However, specific equipment are required for storage, handling, and application. Hence, it is not a popular N carrier in developing countries (Fageria and Baligar, 2005).

The first author conducted field and greenhouse experiments at the National Rice and Bean Research Center of the Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA) to evaluate urea and ammonium sulfate sources of N in lowland rice (Figures 9.15 and 9.16). In both the experiments ammonium sulfate produced higher grain yields than urea at an adequate fertilizer N rate. For example, in the field experiment, 90% of grain yield with ammonium sulfate was obtained at 84 kg N ha^{-1}. While in the case of urea, 90% of the relative grain yield was obtained with the application of 128 kg N ha^{-1}. Similarly, in the greenhouse experiment the response of rice to two sources was similar but ammonium sulfate produced higher grain yields than urea at an adequate N rate. At the highest N rate both the sources produced equal grain yields in field as well as greenhouse experiments. The superiority of ammonium sulfate compared to urea may be associated with the acidifying effects of ammonium sulfate in the oxidized surface layer of the soil and/or in the oxidized layer surrounding the roots, which might have increased the availability of micronutrients. In addition, rice is tolerant to soil acidity and its yield is not adversely affected by soil acidification (Fageria and Baligar, 1999b).

Nitrogen fertilizers are normally broadcast and mixed into the soil before sowing. They may also be applied in the rows below the seed at sowing and may be banded beside the seed at planting or before emergence. After emergence, fertilizers may be sidedressed, injected into the subsurface, or top dressed. Mixing fertilizers into the soil or injecting them below the surface are more efficient methods of N application than broadcasting them onto the soil surface. The placement of urea or

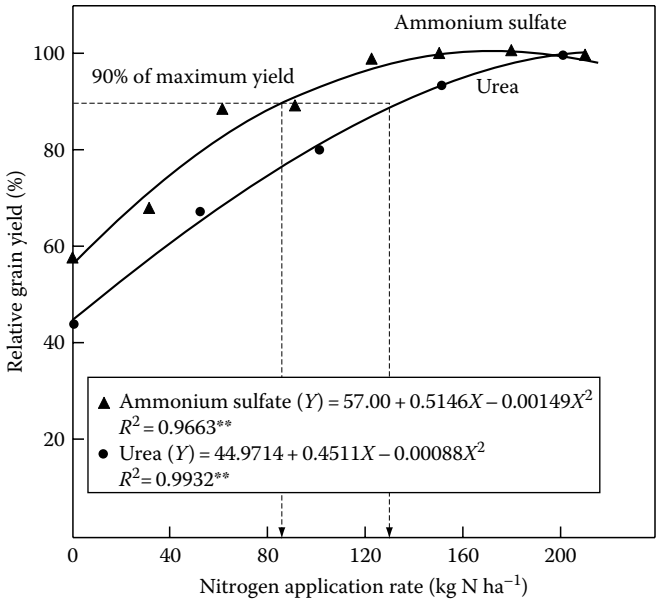

FIGURE 9.15 Grain yield of lowland rice as influenced by nitrogen sources under field conditions, ** significant at the 1% probability level. (From Fageria, N.K. et al., *J. Plant Nutr.*, 32, 2010a, in press.)

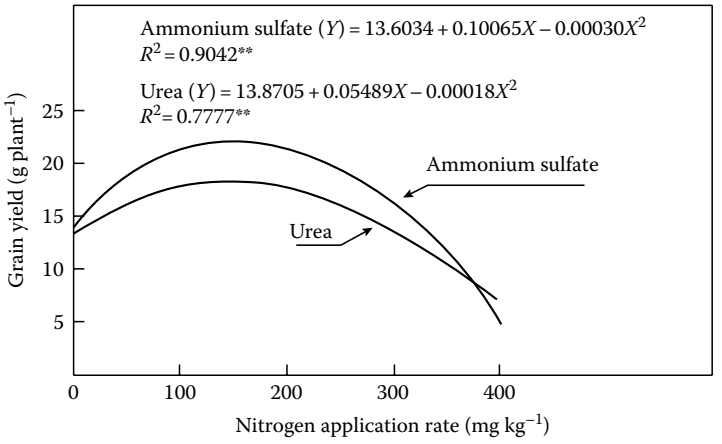

FIGURE 9.16 Grain yield of lowland rice as influenced by nitrogen sources under greenhouse conditions, ** significant at the 1% probability level. (From Fageria, N.K. et al., *Commun. Soil Sci. Plant Anal.*, 40, 2010b, in press.)

ammonium sulfate into the anaerobic layer of flooded rice is an important strategy to avoid N losses by nitrate leaching and denitrification (Fageria and Baligar, 2005).

9.8.4 Use of N-Efficient Genotypes

The use of cultivars that are efficient in the absorption and utilization of N can significantly improve the crop's N use efficiency and profitability. Differences in N uptake and utilization among lowland rice genotypes have been reported by many workers (Fageria and Baligar, 1993, 2005; Fageria et al., 2003). Similarly, studies have shown significant differences in nitrogen use efficiency among rice genotypes in tropical (Singh et al., 1998), subtropical (Ying et al., 1998), and Mediterranean environments (Koutroubas and Ntanos, 2003). Figure 9.17 shows the responses of five lowland rice

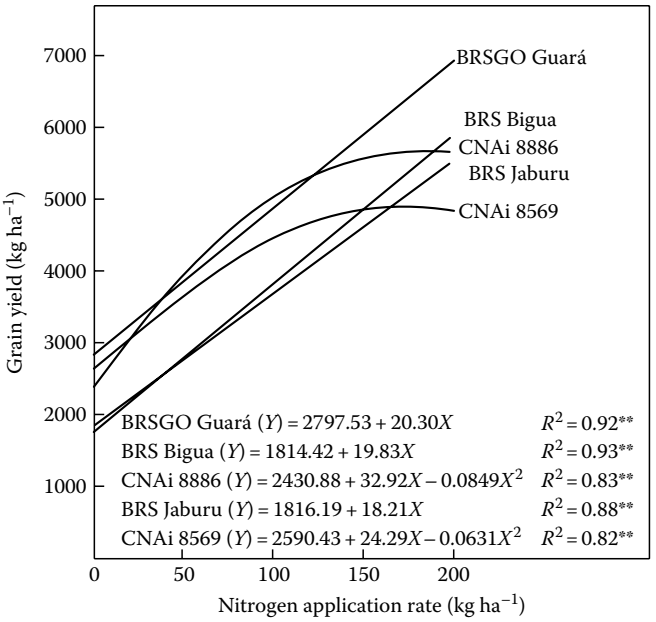

FIGURE 9.17 Response of lowland rice genotypes to nitrogen fertilization, ** significant at the 1% probability level. (From Fageria, N.K. et al., *J. Plant Nutr.*, 31, 1121, 2008a.)

genotypes to N fertilization. These genotypes can be grouped into three classes according to their response to N fertilization. The first group was efficient and responsive and was represented by the genotype BRSGO Guará. It produced a greater yield at the low N level and responded well to applied N. The second group, CNAi 8886 and CNAi 8569, was efficient and nonresponsive, producing well at low N rates but not responding well at higher N rates. The third group is represented by genotypes BRS Bigua and BRS Jaburu, which produce low yields at low N rates but respond well at higher N rates. This genotype can be designated as inefficient and responsive.

From a practical point of view, the genotypes that fall into the efficient and responsive group are the most desirable because they can produce well at low soil N levels and also respond well to applied N. The second most desirable group is efficient and nonresponsive, which are well adapted to low soil N fertility. The inefficient responsive genotypes can be used in breeding program for their N-responsive characteristics.

Several reasons have been proposed for why some genotypes more efficiently utilize N than others (Fageria and Baligar, 2003). Breeders have found that the heritability of grain yield is lower under low N fertility than under high N fertility (Rosielle and Hamblin, 1981). Banziger and Lafitte (1997) reported that the consideration of secondary traits (ears per plant, leaf senescence, leaf chlorophyll concentration) can increase the efficiency of selection for grain yield when broad-sense heritability for grain yield is low under low N fertility.

9.8.5 Nitrogen Use Efficiency

Nitrogen use efficiency is an important indicator of how fertilizer N is used by a crop. Nitrogen use efficiency has been defined and calculated in several ways. Fageria and Baligar (2005) described five definitions and methods of calculating N use efficiency in crops: agronomic efficiency (AE), physiological efficiency (PE), agrophysiological efficiency (APE), apparent recovery efficiency (ARE), and utilization efficiency (UE). Definitions of these efficiencies and their methods of calculation are given in Table 9.16. Fageria et al. (2007) found distinct differences among genotypes in these five N use efficiencies for several lowland rice genotypes (Table 9.17). Overall, 29% of the fertilizer N was

TABLE 9.16
Definitions and Methods of Calculating Nitrogen Use Efficiency

Nutrient Efficiency	Definitions and Formulas for Calculation
Agronomic efficiency (AE)	The agronomic efficiency is defined as the economic production obtained per unit of nutrient applied. It can be calculated by: $$\text{AE (kg kg}^{-1}) = \frac{G_f - G_u}{N_a}$$ where G_f is the grain yield of the fertilized plot (kg); G_u is the grain yield of the unfertilized plot (kg); N_a is the quantity of N applied (kg)
Physiological efficiency (PE)	Physiological efficiency is defined as the biological yield obtained per unit of nutrient uptake. It can be calculated by: $$\text{PE (kg kg}^{-1}) = \frac{BY_f - BY_u}{N_f - N_u}$$ where BY_f is the biological yield (grain plus straw) of the fertilized plot (kg); BY_u is the biological yield of the unfertilized plot (kg); N_f is the N uptake (grain plus straw) of the fertilized plot (kg); N_u is the N uptake (grain plus straw) of the unfertilized plot (kg)
Agrophysiological efficiency (APE)	Agrophysiological efficiency is defined as the economic production (grain yield in case of annual crops) obtained per unit of nutrient uptake. It can be calculated by: $$\text{APE (kg kg}^{-1}) = \frac{G_f - G_u}{N_{uf} - N_{uu}}$$ where G_f is the grain yield of fertilized plot (kg); G_u is the grain yield of the unfertilized plot (kg); N_{uf} is the N uptake (grain plus straw) of the fertilized plot (kg); N_{uu} is the N uptake (grain plus straw) of unfertilized plot (kg)
Apparent recovery efficiency (ARE)	Apparent recovery efficiency is defined as the quantity of nutrient uptake per unit of nutrient applied. It can be calculated by: $$\text{ARE (\%)} = \frac{N_f - N_u}{N_a} \times 100$$ where N_f is the N uptake (grain plus straw) of the fertilized plot (kg); N_u is the N uptake (grain plus straw) of the unfertilized plot (kg); N_a is the quantity of N applied (kg)
Utilization efficiency (UE)	Nutrient utilization efficiency is the product of physiological and apparent recovery efficiency. It can be calculated by: $$\text{UE (kg kg}^{-1}) = \text{PE} \times \text{ARE}$$

recovered, indicating that a large amount of N can be lost in lowland rice systems and appropriate management practices are necessary to improve efficiency.

9.8.6 Nitrogen Harvest Index

Nitrogen harvest index (NHI) is the percentage of total shoot N that is found in the grain at harvest. Nitrogen remobilized from storage tissues is an important source of N in the grain. Grain NHI varies among genotypes and appears to be under genetic control (Fageria and Baligar, 2005). This index is very useful and indicates how efficiently the plant utilized the N it had absorbed for grain

TABLE 9.17
Nitrogen Use Efficiency by Five Lowland Rice Genotypes

Genotype	AE (kg kg^{-1})	PE (kg kg^{-1})	APE (kg kg^{-1})	ARE (%)	EU (kg kg^{-1})
CNAi 8886	23	105	56	37	39
CNAi 8569	17	188	69	29	55
BRSGO Guará	21	222	123	29	64
BRS Jaburu	16	114	64	26	30
BRS Biguá	19	145	74	23	33
Average	19	155	77	29	44

Source: Adapted from Fageria, N.K. et al., *Pesq. Agropec. Bras*., 42, 1029, 2007.

production (Fageria and Baligar, 2005). Genetic variability in NHI has been found among crop species and among genotypes. Among genotypes, high NHI is associated with the efficient utilization of N (Fageria and Baligar, 2005). In addition, NHI may be useful in selecting crop genotypes for higher grain yield. In lowland rice NHI varied from 0.53 to 0.64 among genotypes (Fageria, 2007).

9.9 MANAGEMENT OF PHOSPHORUS IN LOWLAND RICE

After N, P is the second most important nutrient limiting rice yield, especially in acid soils. This means that producing good crop yields on these soils requires good P management. The use of an adequate level of P for maximum yield is possible if P soil test calibration data are available for a given crop and soil type. The amount of nutrient extracted in a soil is of little use until it has been calibrated to crop response in field experiments. Figure 9.18 shows lowland rice grain yield as a function of phosphorus applied in an Inceptisol. Grain yield increased with broadcast P fertilization, with a maximum yield obtained at about 290 kg P ha^{-1}. The relative grain yield of this experiment was plotted against soil extractable P for calibration of soil P test (Figure 9.19).

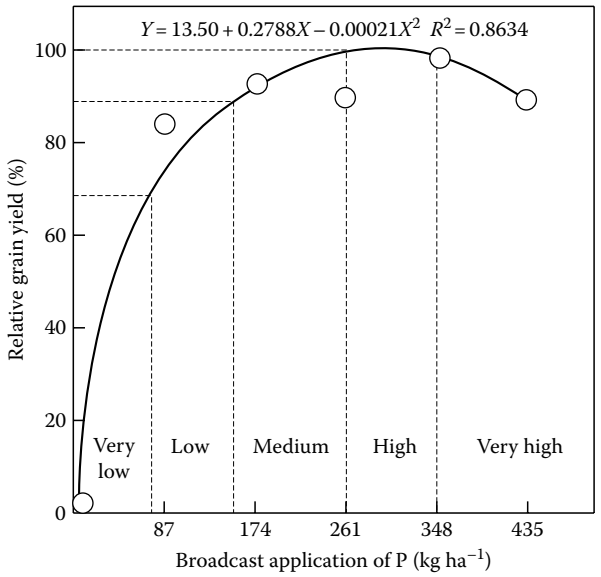

FIGURE 9.18 The relationship between P applied as broadcast and relative grain yield of lowland rice. (From Fageria, N.K., Annual report of the project, The study of liming and fertilization for rice and common bean in Cerrado region, National Rice and Bean Research Center, Goiania, Brazil, 1996.)

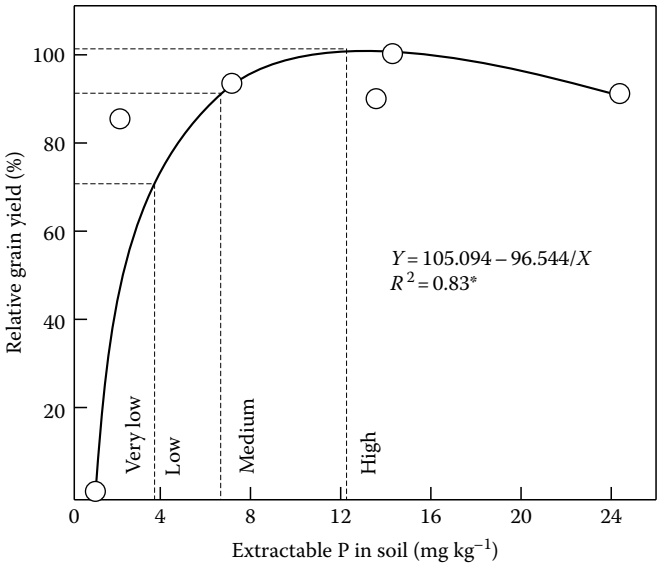

FIGURE 9.19 The relationship between Mehlich-1 extractable P and relative grain yield of lowland rice. (From Fageria, N.K., Annual report of the project, The study of liming and fertilization for rice and common bean in Cerrado region, National Rice and Bean Research Center, Goiania, Brazil, 1996.)

TABLE 9.18
Soil P Test Availability Indices and P Fertilizer Recommendations for Lowland Rice in an Inceptisol

Soil P Test (mg kg^{-1})	Interpretation	Relative Yield (%)	Broadcast P Application (kg ha^{-1})	Band P Application (kg ha^{-1})
0–3.6	Very low	0–70	100	66
3.6–6.4	Low	70–90	170	66
6.4–12.0	Medium	90–100	275	44
>12.0	High	>100	>275	22

Four categories were established for the soil P test: very low (VL), low (L), medium (M), and high (H). The 0%–70% relative yield zone is called VL, the 70%–90% relative yield zone is called L, the 90%–100% relative yield zone is called M, and more than 100% relative yield is called high soil P test. These zones are selected arbitrarily, as suggested by Raij (1991), for a soil P calibration study under Brazilian conditions. The soil P test availability indices and P fertilizer recommendations for the soil under investigation, calculated on the basis of Figures 9.18 and 9.19, are presented in Table 9.18.

9.10 MANAGEMENT OF POTASSIUM IN LOWLAND RICE

Potassium deficiencies in upland as well as lowland rice occur less frequently than N and P deficiencies. However, with the intensive use of soil and high-yielding cultivars, the soil reserves of K may not be sufficient to maintain productivity for a long time. Under these circumstances, the use of K-efficient cultivars can be a complementary solution to overcome K deficiency. Fageria et al. (2010b) studied the response of lowland rice to K fertilization for 2 years on a Brazilian Inceptisol. The (year × K rate) interaction for grain yield was significant, indicating variation in grain yield from year to year hence; therefore, data for each year are presented (Table 9.19). In the first year grain yield varied from 2961 kg ha^{-1} without K fertilizer to 5880 kg ha^{-1} at 125 kg K ha^{-1}, a variation

TABLE 9.19
Grain Yield of Rice as Influenced by Potassium Fertilization

K Rate (kg ha^{-1})	Grain Yield (kg ha^{-1})		
	First Year	Second Year	Average
0	2961	2631	2796
125	5880	6244	6062
250	5526	5590	5558
375	4853	5092	4973
500	4962	5076	5019
625	5091	5329	5210
F-test			
Year (Y)	**		
K rate (K)	**		
Y × K	**		
CV (%)	6.8		

Regression analysis

K rate (X) vs. first year grain yield (Y) = 3641.72 + 10.3063X − 0.0138X^2, R^2 = 0.4466**

K rate (X) vs. second year grain yield (Y) = 3467.83 + 12.3452X − 0.0163X^2, R^2 = 0.4567**

K rate (X) vs. average grain yield (Y) = 3555.04 + 11.3227X − 0.0151X^2, R^2 = 0.4674**

Sources: Fageria, N.K. et al., *Commun. Soil Sci. Plant Anal.*, 40, 2010b, in press.

** Significant at the 1% probability level.

of about twofold. In the second year grain yield varied from 2631 kg ha^{-1} at zero rate of K to 6244 kg ha^{-1} at 125 kg K ha^{-1}, a variation of about 2.4-fold. This variation in grain yield from year to year was expected due to variation in climatic conditions (Fageria, 1992). These results also suggest that field experiments should be repeated in space or time to reach meaningful conclusions for making fertilizer recommendations.

Response of lowland rice to K fertilization has been reported by many workers (Fageria et al., 1990a, 2003). Pretty and Stangel (1985) reported that 17% of the total land area is K deficient in Africa, 21% of total land area is K deficient in Asia, and 29% of the total land area is K deficient in Latin America. Most of the K-deficient soils in these three continents are acid savanna soils. Buol et al. (1975) estimated that one-fourth of the soils in the tropics and subtropics have a low K status. Fageria et al. (1990a) reported that 50% of the Amazon Basin has soils with low K reserves. Fageria (1989) also reported that many soils of the tropical and temperate regions are unable to supply sufficient K to field crops. Hence, the application of this element in adequate amount is essential to obtain optimal crop yields and maintain soil fertility. Williams and Smith (2001) reported that prior to the early 1990s, K deficiency was rare in the rice-producing areas of the United States. However, K deficiency is now recognized as a common problem on many soils as rice and rotation crop yields have increased, soils have been mined of K, and production practices have changed.

9.10.1 Soil Test Calibration to Potassium

The results of K soil test calibration are presented in Figure 9.20. There was a nonlinear response to Mehlich-1 extractable K in the range of 14–86 mg K kg^{-1} in the first year. In the second year rice

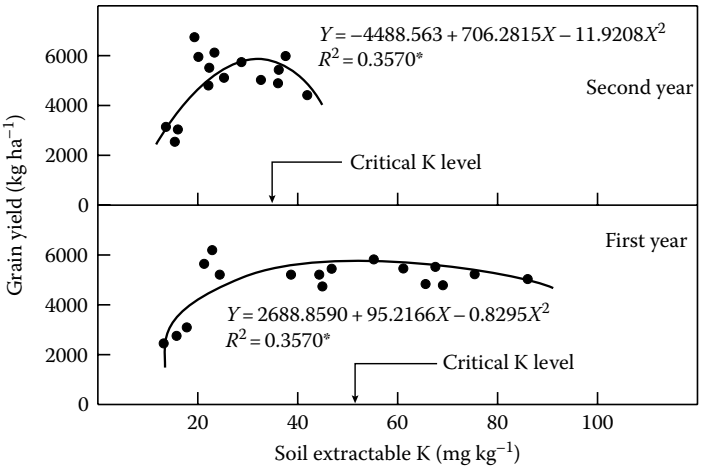

FIGURE 9.20 Relationship between soil extractable potassium and grain yield of lowland rice. (From Fageria, N.K. et al., *Commun. Soil Sci. Plant Anal.*, 40, 2010b, in press.)

yield responded to fertilizer K when soil test K was in the range of 15–42 mg kg^{-1}. In the first and second years, maximum grain yields were obtained at 57 and 30 mg K kg^{-1} of soil, respectively. In a similar study, Fageria et al. (1990a) reported that the Mehlich-1 extractable soil K level associated with maximum rice yield was 59 mg kg^{-1} for the first crop and 34 mg kg^{-1} for the second crop on a Brazilian Inceptisol. The maximum grain yield obtained at the low soil test K level (30 mg kg^{-1}) in the second year suggests that in the second year non-exchangeable K might have played an important role in the supply of K to the rice crop. Sparks (1987) and Hinsinger (1998) reported that the availability of non-exchangeable K to plants is associated with very low level of K in the soil, possibly due to chemical changes in the rhizosphere.

9.11 CALCIUM, MAGNESIUM, AND SULFUR

Reports of calcium, magnesium, and sulfur deficiencies in lowland rice are infrequent. However, deficiencies of these elements in upland rice are quite common in tropical soils (Fageria, 1984a; Fageria and Morais, 1987; Islam et al., 1987; Malavolta et al., 1987). Fageria (1984b) and Fageria and Morais (1987) reported different responses of upland rice cultivars to calcium and magnesium in Oxisols of central Brazil. The deficiency of Ca and Mg can be corrected by the application of dolomitic lime. Generally, 3–4 Mg ha^{-1} is sufficient to correct Ca and Mg deficiencies in upland as well as lowland rice. Sulfur deficiency can be corrected by the application of ammonium sulfate at the rate of 100 kg ha^{-1}.

9.12 MANAGEMENT OF MICRONUTRIENTS IN LOWLAND RICE

Micronutrient deficiencies occur in crop plants in various parts of the world (Fageria et al., 2002), often due to the use of high-yielding cultivars and liming to raise soil pH, which reduces the availability of most micronutrients. The deficiencies of Zn and B are commonly found in lowland rice. A detailed discussion of micronutrient management in crop plants is given by Fageria et al. (2002, 2003).

9.12.1 Zinc

Zinc deficiency has been reported in various parts of the world for a large number of annual crops, including rice (Cakmak et al., 1998; Mandal et al., 2000; Fageria, 2001b; Fageria et al., 2003).

A global study by Food and Agriculture Organization (FAO) in the 1980s showed that about 30% of the cultivated soils of the world were Zn deficient (Sillanpaa, 1982). Additionally, about 50% of the soils used worldwide for cereal production contain low levels of plant-available Zn (Graham et al., 1992; Welch, 1993). De Datta (1981) reported that Zn deficiency is the second most serious nutritional disorder limiting yields of lowland rice in the Philippines. Slaton et al. (2005) reported that zinc is the most common micronutrient applied to rice in the United States. Zinc deficiency in crop plants reduces not only grain yield but also the nutritional quality of the grain. The consumption of large quantities of cereal-based foods with low Zn concentrations, poor bioavailability of Zn, or both is thought to be a major factor in the widespread occurrence of Zn deficiency in humans (Welch, 1993). In Brazil, Zn deficiencies have been reported in upland as well as lowland rice (Fageria et al., 2003; Fageria and Stone, 2008). Deficiencies are related both to low concentrations of Zn in the highly weathered soils used for rice production and to excessive lime application (Fageria and Baligar, 1993; Fageria and Gheyi, 1999). Zinc deficiency can be corrected by the application of 5 kg Zn ha^{-1} as zinc sulfate.

9.12.2 Boron

Boron deficiency has been reported in at least 80 countries and 132 crop species. It is estimated that about 15 million ha are annually treated with B fertilizers (Shorrocks, 1997). Plant species vary in their B requirements, with dicotyledons generally requiring three to four times more B than monocotyledons (Bennett, 1993). A number of soil properties influence B availability to plants and are reviewed by Fageria et al. (2002). Coarse-textured, low organic matter soils located in humid regions are the most prone to B deficiency. The application of lime to acid soils can also induce B deficiency because of increased B adsorption at high soil pH. Known boron deficiencies are not common in rice, but several environmental (i.e., high rainfall), soil (i.e., low organic matter, texture, and pH), and rice production (i.e., flood irrigation) factors common to many rice-growing regions of the world hint that B could limit yields. Our lack of understanding of the B nutritional requirements, seasonal patterns of B uptake, and B partitioning within the rice plant demonstrates the need for increased research on this micronutrient.

9.13 NUTRIENT CONCENTRATION AND UPTAKE

Plant analysis is an accepted means of predicting fertilizer requirements and of diagnosing nutrient deficiencies based on critical or adequate nutrient values (Fageria, 2009). The N content of rice at the panicle formation stage (about 10–15 days before flowering) has been shown to be an important determinant of sink size and eventual yields (Sheehy et al., 2005). Adequate nutrient concentrations for rice are presented in Table 9.20.

The accumulation of N, P, K, Ca, Mg, Fe, Cu, Mn, B, and Zn in lowland rice during crop growth is presented in Figure 9.21. The accumulation pattern of nutrients was similar to that of dry matter accumulation. The quantity of nutrients accumulated was in the order of K > N > P > Ca > Mg for macronutrients and Mn > Fe > Zn > Cu > B for micronutrients. At the time of harvest, 64% N, 74% P, 15% K, 15% Ca, 58% Mg, 50% Zn, 16% Mn, 94% Cu, 64% Fe, and 47% B were exported to grains. De Datta and Mikkelsen (1985) reported similar quantities of these nutrients exported to lowland rice grains. These and other nutrients removed from the soil by the crop must be replenished to sustain high production.

9.14 IRON DEFICIENCY AND TOXICITY IN LOWLAND RICE

Iron toxicity in lowland rice has been reported in Southeast Asia, Africa, and South America (Howeler, 1973; Virmani, 1977; Ottow et al., 1982; Fageria and Rabelo, 1987; Fageria et al., 2008b). The solubility of iron in soils is controlled by $Fe(OH)_3$ in well-oxidized soils, by $Fe_3(OH)_8$

TABLE 9.20
Adequate Nutrient Concentrations for Rice

Nutrient	Growth Stage	Plant Part	Adequate Concentrations (g kg^{-1})
N	Heading	Uppermost mature leaves	26–42
P	75 DAS[a]	Whole tops	2.5–4.8
K	75 DAS	Whole tops	15–40
Ca	100 DAS	Whole tops	2.5–4
Mg	100 DAS	Whole tops	1.7–3
S	Tillering	Uppermost mature leaves	2–6
			(mg kg^{-1})
Fe	Tillering	Whole tops	70–300
Zn	Tillering	Whole tops	20–150
Mn	Tillering	Whole tops	30–600
B	Tillering	Uppermost mature leaves	20–100
Cu	Tillering	Uppermost mature leaves	5–20
Mo	Tillering	Uppermost mature leaves	0.5–2

Source: Fageria, N.K., *Fertilization and Mineral Nutrition of Rice*, EMBRAPA-CNPAF/Editora Campus, Rio de Janeiro, Brazil, 1984a.

[a] DAS = days after sowing.

(ferrosic hydroxide) in moderately oxidized soils, and by $FeCO_3$ (siderite) in highly reduced soils (Lindsay and Schwab, 1982). The Fe^{3+} hydrolysis species, $Fe(OH)_2^+$ and $Fe(OH)_3^0$, are the major solution species of inorganic Fe, but their concentrations are too low to supply available iron to plants. Iron is absorbed by plants as Fe^{2+} and must be in the general range $>10^{-7.7}$ M to avoid iron deficiency. The redox potential of the soil-root environment must be <12 to supply adequate Fe^{2+} for plants (Lindsay and Schwab, 1982; Fageria et al., 2008b).

The concentration of water-soluble iron, which before submergence rarely exceeds 0.1 mg kg^{-1}, may rise to a peak value of 600 mg kg^{-1} within 2 weeks after submergence and then gradually decrease to values ranging from 20 to 100 mg kg^{-1} (Ponnamperuma, 1977b). In acid sulfate soils containing high levels of reactive iron oxides, the concentrations of water-soluble iron can be as high as 5000 mg kg^{-1} (Ponnamperuma, 1977b). The toxic levels of Fe for rice have been reported to be 300–500 mg kg^{-1} in the soil solution (Tanaka et al., 1966) and 300–600 mg kg^{-1} in rice leaves (Tanaka et al., 1966; Fageria et al., 1981a, 2008b). Low temperature and the presence of $CaCO_3$ and nitrates tend to retard the decrease in soil Eh and the initial increase in water-soluble iron, but this effect may disappear with time (Savant and McClellan, 1987). In a rice soil, 5%–50% of the free iron oxides may be reduced within a few weeks of submergence (Ponnamperuma, 1972). According to Ponnamperuma (1978), the increase in the concentration of water-soluble Fe^{2+} after submergence can be described for most of the mineral soils by the equation

$$Eh = 1.06 - 0.059 \log Fe^{2+} - 0.177\ pH\ 1$$

9.14.1 Iron Uptake Mechanisms

In oxidized soils Fe is generally in the ferric form (Fe^{3+}), it is tied up with oxides and hydroxyoxides, and its solubility is low. However, the major form of iron taken up by plants is the ferrous (Fe^{2+})

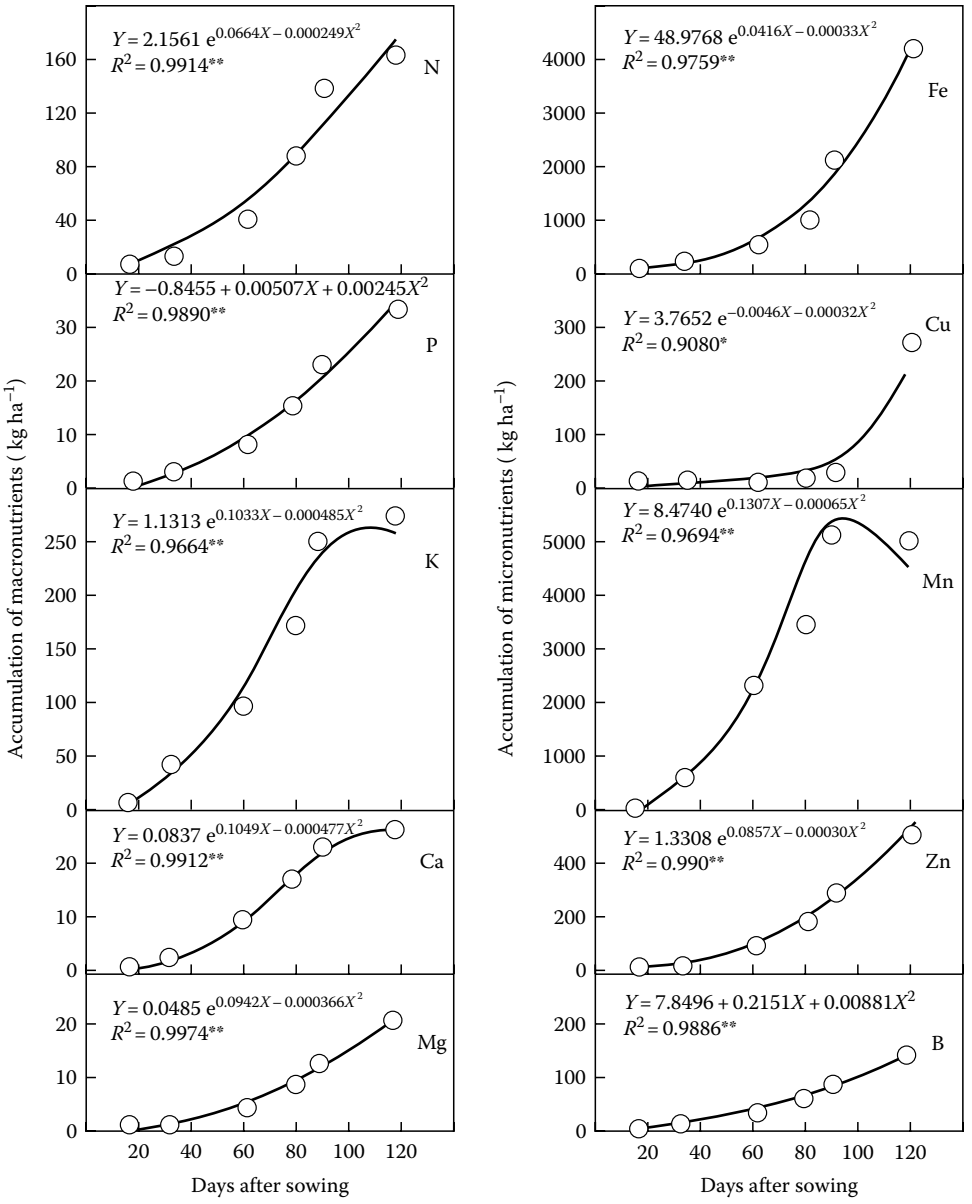

FIGURE 9.21 Nutrient accumulation in lowland rice crop during the growth cycle, ** significant at the 1% probability level. (From Fageria, N.K., Annual report of the project, The study of liming and fertilization for rice and common bean in Cerrado region, National Rice and Bean Research Center, Goiania, Brazil, 1996.)

ion (Lindsay and Schwab, 1982). Hence, iron has to be reduced to the Fe^{2+} form for uptake by crop plants, or Fe^{3+} has to be absorbed by the roots in association with chelating agents (Romheld and Marschner, 1986; Rogers and Guerinot, 2002; Epstein and Bloom, 2005). Plants can release protons (H^+) from their roots and thereby lower the pH of rhizosphere. The lower pH of the rhizosphere may solubilize or reduce Fe^{3+} to the Fe^{2+} form. The reduced iron is then transported across the plasma membrane by a Fe^{2+}-specific transport system. This type of mechanism mainly operates in the dicots and non-graminaceous monocots (Epstein and Bloom, 2005).

The second mechanism induced by crop plants for uptake of iron is the release of phytosiderophores (iron carriers) by plant roots. These phytosiderophores form a complex with Fe^{3+} ion without

reducing it to Fe^{2+}, and this Fe^{3+}-siderophore complex is then transported across the root cell plasma membranes (Epstein and Bloom, 2005). Takagi et al. (1984) showed that the release of chelating compounds or phytosiderophores occurs in grasses but not the dicots. The chelating compounds are characterized as nonprotein amino acids, mugineic, and avenic acids. The pathways for biosynthesis of these acids are still not known, but these amino acids are structurally related to nicotianamine, a compound found primarily in the shoots of green plants that has been shown to induce regreening of a chlorotic mutant of tomato, possibly through mobilizing Fe for intercellular and intracellular transport (Kochian, 1991).

9.14.2 Factors Inducing Iron Toxicity

Factors, which affect solubility and concentration of iron in the rice rhizosphere, may influence its availability. If these factors cause greater uptake than plant demand, iron toxicity may occur. Soil conditions important to the solubility and availability of iron to plants have not been fully defined, largely because solubility and availability relationships for iron are very complex (Fageria et al., 1990b). However, factors associated with iron toxicity include: release of iron from parent material to soil solution, reduction in oxidation–reduction potential, increase in the ionic strength of the soil solution, low soil fertility, low soil pH, high soil organic matter content and microbial activity, interaction with other nutrients, and genotypic susceptibility.

9.14.2.1 Release of Iron from Parent Material in Soil Solution

Iron is a major constituent of most soils. Iron minerals commonly found in soils include geothite (FeOOH), hematite (Fe_2O_4), pyrite (FeS), siderite ($FeCO_3$), and magnetite (Fe_3O_4) (Fageria et al., 2003). The weathering of parent material can release significant amount of nutrients in the soil solution, including iron. When the Fe^{2+} concentration of reduced or submerged soils is high, its uptake may be in excess than plant demand and may produce toxicity in rice plants. In West Africa, bronzing occurs in rice plants grown in inland valley swamps, irrigated lowlands, and hydromorphic lands (International Institute of Tropical Agriculture, 1983). A study in Nigeria indicated that the occurrence of bronzing was positively correlated with the ferrous iron concentration in the soil, suggesting that the disorder was caused by iron toxicity (Kosaki and Juo, 1986).

9.14.2.2 Oxidation–Reduction Potential

Oxidation–reduction or redox potential has significant influence on the chemistry of iron and other nutrients in the submerged soils. It is the best single indicator of the degree of anaerobiosis in the flooded soil, and allows reasonable predictions to be made concerning the behavior of several essential plant nutrients (Patrick and Mikkelsen, 1971). Oxidation–reduction is a chemical reaction in which electrons are transferred from a donor to an acceptor. The electron donor loses electrons and increases its oxidation number or is oxidized, the acceptor gains electron, and decreases its oxidation number or is reduced. The source of electrons for biological reductions is organic matter (Ponnamperuma, 1972). Oxidation–reduction affects the valence of iron and thereby its uptake by plants. The Fe^{3+} ion is reduced to Fe^{2+} due to oxidation–reduction processes and the Fe becomes much more available for plant uptake. On the other hand, when Fe^{2+} is oxidized to Fe^{3+}, its concentration is reduced and uptake by plants is also reduced. The reduction of Fe^{3+} to Fe^{2+} is expressed by the following equation (Ponnamperuma, 1977a):

$$Fe(OH)_3 + 3H^+ + e^- \Leftrightarrow Fe^{2+} + 3H_2O$$

In addition to reduction of Fe^{3+} to Fe^{2+}, in submerged soils Mn^{4+} is reduced to Mn^{2+}, NO_3^- to N_2, SO_4^{2-} to H_2S, CO_2 to CH_4, and H^+ to H_2. All these reduction processes influence Fe^{2+} concentration in the soil solution and consequently its uptake by rice plants. Reduction processes in the submerged

or flooded soils are influenced by the magnitude of oxidation–reduction, which is measured in millivolts. The critical redox potentials for Fe reduction and consequent dissolution are between +300 mV and +100 mV at pH 6 and 7, and −100 mV at pH 8, while at pH 5 appreciable reduction occurs at +300 mV (Gotoh and Patrick, 1976).

9.14.2.3 Soil pH

Soil pH is an important chemical property, which determines iron solubility and its uptake by plants. In addition, soil pH is often highly changeable property because of the dynamic nature of soil processes and the interactions of these processes with plants and microorganisms (Adams, 1984). As pH increases, Fe is converted to less soluble forms, principally to the oxide Fe_2O_3. The reaction responsible for the reduced solubility of Fe with increasing pH is well understood. As pH and the concentration of OH^- ions increases, Fe^{3+} is precipitated as $Fe(OH)_3$, as indicated by the following reaction (Fageria et al., 1990b):

$$Fe^{3+} + OH^- \Leftrightarrow Fe(OH)_3$$

The $Fe(OH)_3$ is chemically equivalent to the hydrated oxide, $FeO_3 \cdot 3H_2O$. Acidification shifts the equilibrium, causing a greater release of Fe^{3+} as a soluble ion. This means that iron toxicity is more severe in acid soils than in alkaline soils. The overall effect of submergence is to increase the pH of acid soils and to depress the pH of sodic and calcareous soils (Ponnamperuma, 1972). The magnitude of pH increase or decrease depends on soil type, organic matter content, soil fertility, crop rotation, and rice cultivar. Soils high in organic matter content and reducible iron attain a pH of about 6.5 within a few weeks of submergence. Acid soils low in organic matter or active iron slowly attain pH values less than 6.5 (Ponnamperuma, 1972). The increase in pH of acid soils due to submergence is associated with the reduction process and the decrease in pH of alkaline soils is due to accumulation of CO_2.

All the reduction reactions consume H^+ ions, producing a decrease in acidity and an increase in OH^- ions. Most soils contain more Fe^{3+} hydrates than any other oxidant, and the increase in pH of acid soils when they are submerged is largely associated with iron reduction (Ponnamperuma, 1972). The increase in pH of acid soils after submergence has beneficial effects on rice growth by reducing Al^{3+} and Fe^{2+} toxicity and increasing P availability. Breemen and Moormann (1978) reported that iron toxicity has been observed only in flooded soils with a pH below 5.8 when aerobic, and pH below 6.5 when anaerobic. These authors also reported that in most flooded soils that have an aerobic pH below 5.8, the concentration of iron reaches high levels for only a short period. But in young acid sulfate soils, iron concentrations can exceed 500 mg kg^{-1} for prolonged periods.

9.14.2.4 Ionic Strength

Ionic strength is a measure of the electrical environment of ions in a solution, and it is calculated as follows (Fageria et al., 2008b):

$$\text{Ionic strength} = \frac{1}{2}\sum M_i Z_i^2$$

where

M_i is the molarity of ion i

Z_i is the total charge of ion i (regardless of sign)

Σ is a symbol meaning the "sum of"

The ionic strength of submerged soils increases with the release of macro- and micronutrients in the soil solution (Patrick and Mikkelsen, 1971). The increase in ionic strength increases Fe^{2+} uptake by rice plants and may produce Fe toxicity. When acid soils are submerged, the increase in ionic

strength is associated with reduction to Fe^{2+} and Mn^{2+} and solubilization of P. In alkaline soils, submergence causes an increase in ionic strength associated with the displacement of cations by ferrous iron produced through reduction reactions (Patrick and Mikkelsen, 1971).

9.14.2.5 Low Soil Fertility

An important factor in improving crop productivity and maintaining ecosystem stability is adequate levels of essential nutrients in soils. Deficiency of any essential element, such as potassium, phosphorus, calcium, or magnesium, may increase uptake of Fe^{2+} by rice and cause iron toxicity in lowland rice (Tadano and Tanaka, 1970; Tadano, 1975). Yamauchi (1989) reported that the application of potassium sulfate reduced the severity of bronzing due to Fe toxicity and increased the dry matter production of rice plants grown in the field. The concentration and accumulation of potassium in the shoots increased when the bronzing severity decreased and the iron concentration was decreased by the dilution effect caused by the increased dry matter production (Yamauchi, 1989).

The oxidizing capacity of the rice root, which causes oxidation and precipitation of part of the ferrous iron, is important in depressing the uptake of Fe^{2+} present in high concentrations in the root zone (Tadano, 1975). Trolldenier (1977) reported that low potassium and phosphorus may aggravate iron toxicity by decreasing the oxidizing capacity of the roots. In contrast, nitrogen deficiency does not result in higher iron uptake. Trolldenier (1977) reported that higher N fertility might even stimulate uptake of excess iron. High salinity due to sodium chloride or magnesium chloride also increases iron uptake and may thus aggravate iron toxicity (Breemen and Moormann, 1978).

9.14.2.6 Interaction with Other Nutrients

Iron interaction with other nutrients may be antagonistic, synergistic, or neutral, depending on the growth response of plants. If the growth response is greater with two combined factors as compared to the sum of their individual effects, it is a positive interaction, and when the combined effects are less, the interaction is negative (Sumner and Farina, 1986; Fageria et al., 1990b). Nutrient interaction is also measured in terms of influence of one nutrient on the uptake of other nutrients. Antagonistic interactions with other nutrients reduce Fe availability to rice and vice versa. The antagonistic or negative interactions may result from interactions that occur either outside the root or within the root. Those taking places in the external root environment include precipitation or similar reactions that reduce the chemical availability of the nutrient. Reactions that reduce absorption or utilization processes reduce the nutrient's physiological availability (Fageria et al., 1990b).

Manganese often exhibits an antagonistic interaction with iron in rice (Olsen and Watanable, 1979). The application of Mn to soils significantly reduces the uptake of iron by rice. Similarly, Fe can exhibit antagonistic interactions with macronutrients. Fageria et al. (1981a) reported that uptake of P, K, Ca, and Mg decreased in the nutrient solution with the increasing Fe concentration in the range of 0–160 mg Fe L^{-1}.

9.14.3 Physiological Disorders Related to Iron Toxicity

Iron toxicity causes several physiological disorders in rice plants, including *bronzing, akagare type I,* and *akicochi* (Yoshida, 1981; Tadano, 1995). Bronzing is discoloration of rice leaves. Many small brown spots appear on the leaves. These symptoms start on the tips of lower leaves and spread to the basal parts. In severe cases, the brown discoloration appears even on the upper leaves. The bronzing symptoms vary among cultivars and may be purplish orange, yellowish brown, reddish brown, brown, or purplish brown (Tadano, 1995).

Akagare type I disorder caused by Fe toxicity in rice has been reported in Japan, South Korea and Sri Lanka (Tadano, 1995). The symptoms of this disorder are dark green leaves with small reddish brown spots around the tips of older leaves. Under severe Fe toxicity, the spots spread all over

the leaves and the leaves die back from the tips. The roots of affected plants turn light brown or dark reddish brown or blackened, depending on soil type. Yoshida (1981) reported that the main reason of akagare disorder is K deficiency aggravated by Fe toxicity.

The symptoms of akicochi disorder in rice include small brown spots on the older leaves that may spread to the whole plant under severe iron toxicity. Akicochi disorder symptoms are similar to those of helminthosporium, a fungus disease of rice. Akicochi disorder mainly occurs when soils are deficient in Si and K. The presence of adequate amounts of Si and K in the soil solution increases the oxidizing power of rice roots and decreases excessive Fe uptake (Tadano, 1976; Yoshida, 1981). The application of Si is normally considered beneficial when the Si content in rice straw is lower than 11% (Yoshida, 1981). Similarly, the application of fertilizer K is beneficial when the K content of rice soils is lower than 60 mg kg^{-1} (Fageria, 1984a).

9.14.4 Management Practices to Ameliorate Iron Toxicity

Effective measures to ameliorate Fe^{2+} toxicity include periodic surface drainage to oxidize reduced Fe^{2+}, liming acid soils, use of adequate amounts of essential nutrients, and planting cultivars/genotypes resistant to Fe toxicity. The Fe-excluding ability of rice plants is lowered by deficiencies of P, K, Ca, and Mg (Obata, 1995). In particular, K deficiency readily induces Fe toxicity (Fageria et al., 2003). Among these management practices, use of tolerant cultivars is most economical and environmentally sound practice (Fageria et al., 1984, 1990a; Fageria and Rabelo, 1987). Tadano (1976) suggested three mechanisms that may be for variation in resistance to Fe toxicity in rice cultivars. These include (1) oxidation of Fe^{2+} in the rhizosphere, (2) exclusion of Fe^{2+} at the root surface, and (3) retention of Fe in the root tissues, which prevents translocation of Fe from the root to the shoot. The introduction of modern high-yielding cultivars has often led to an increase in the incidence of bronzing, apparently because the traditional cultivars have better tolerance of iron toxicity and other adverse soil conditions (Breemen and Moormann, 1978).

9.15 SALINITY

Salinity is an important growth-limiting factor for rice production in arid and semiarid regions, where potential evaporation is substantially higher than precipitation. As a result, salts are not leached from the soil, and they accumulate to levels detrimental to crop growth. Soils are also salinized by tides in coastal areas and by irrigation water in areas where irrigation water contains high levels of dissolved solids. It has long been known that grain yield in rice is more sensitive to salinity during the seedling and grain-filling stages than during the later stages of vegetative growth (Pearson, 1961; Flowers and Yeo, 1981). It has recently been observed that excessive salinity during panicle initiation has a particularly marked effect on the reproductive growth of rice (Khatun and Flowers, 1994).

Khatun et al. (1995) assessed the effects of salinity on rice genotypes. Salinity delayed flowering and reduced the number of productive tillers, panicle length, the number of priary panicle branches, the number of fertile florets per panicle, the weight per grain, and the grain yield. The effects of salinity on grain yield were much more severe than on vegetative growth. Genetic variation in the response of these characters to salinity was also observed.

Table 9.21 shows the relative tolerance of important field crops to salinity. Among these crops, barley and cotton are most tolerant to soil salinity and common bean (*Phaseolus vulgaris* L.) is most susceptible to salinity stress. Rice is moderately susceptible to soil salinity, but differences exist among cultivars (Fageria et al., 1981b; Yeo and Flowers, 1982; Fageria, 1985).

The resistance to salinity by rice is not determined by a single heritable character, but is a complex whole-plant phenomenon involving many interacting processes. Consequently, it has been suggested (Yeo and Flowers, 1986; Yeo et al., 1990) that the resistance to saline conditions can be increased beyond the existing phenotypic range by selecting individual physiological traits that contribute

TABLE 9.21
Salt Tolerance of Important Field Crops

Crop	Salinity at Initial Yield Decrease (dS m^{-1})	Salinity at Which 25% Yield Decrease (dS m^{-1})	Salinity at Which 25% Yield Decrease (dS m^{-1})	Classification[a]
Rice	3	6	8	MS
Wheat	6	10	14	MT
Corn	2	6	7	MS
Sorghum	—	9	12	MS
Barley	8	16	18	T
Soybean	5	7	9	MT
Common bean	1	2	3	S
Alfalfa	2	5	8	MS
Cotton	7.7	12	16	T
Potato	1.7	4	6	MS
Sugarcane	1.7	5	8.5	MS

Sources: Compiled from Bernstein, L., Salt tolerance of plants, USDA Information Bulletin 283, U.S. Government Printing Office, Washington, DC, 1964; Maas, E.V. and Hoffman, G.J., *J. Irrig. Drain. Div. Am. Soc. Civil Eng*., 103, 115, 1977.

[a] T = tolerant, MT = moderately tolerant, MS = moderately susceptible, and S = susceptible.

to resistance and combining them in a breeding program. While some of the characters determining resistance at the seedling stage have been described (Yeo et al., 1990), less is known about characters that might be important for grain yield under saline conditions. More is known about seedlings than mature plants because results can be obtained more quickly and easily with small vegetative plants than with large flowering plants (Yeo and Flowers, 1983).

9.16 SUMMARY

After wheat, rice is the most important food crop worldwide. It is a very versatile tropical or warm-season temperate crop that is grown on all continents except Antarctica, but over 90% of world production is in Asia. It is grown from 50°N to 35°S latitude and from sea level to over 3000 m in the Himalayas.

There are two broad types of rice culture, upland and lowland. Upland rice is defined as that grown in rainfed, naturally well-drained soils without surface water accumulation, normally without a phreatic water supply, and normally without bunds. Brazil is the largest producer of upland rice. Lowland rice is grown on somewhat more than 50% of the world's rice-producing area. It is normally cultivated in bunded paddies with some type of controlled irrigation. Lowland rice soils are normally flooded to a depth of 10–15 cm a few weeks after seeding or transplanting and are drained shortly before harvest. Some varieties of floating rice can grow in waters as deep as 4 m.

In recent decades new upland and lowland rice genotypes have been bred to improve grain yield potential. Record upland rice yields under Brazilian conditions are about 5 Mg ha^{-1}. Record lowland rice yields are over 10 Mg ha^{-1}, but farmers' yields are usually much lower. In similar environments, upland rice yields are always lower than lowland rice yields, primarily due to the crop's ability to grow and absorb nutrients at optimal rates in flooded soils. In addition, upland rice is often subjected to diseases and environmental stresses, and it is especially sensitive to blast and drought stress. In Brazil, average upland rice yields are about 2 Mg ha^{-1} and mean lowland rice yields are about 5 Mg ha^{-1}. The development of semidwarf cultivars in the 1960s dramatically increased world rice yields (lowlands), which now average about 3.8 Mg ha^{-1} worldwide.

Rice can be grown on a wide variety of soils, but slowly permeable clay soils are usually more suitable than soils with little water-holding capacity that drain rapidly. Around flowering, rice is particularly susceptible to drought stress, nitrogen deficiency, blast disease, and low solar radiation. Flooding paddy soils causes a number of electrochemical changes in the soil that, in general, benefit the crop. Many nutrients become more easily available to the crop, and most nutrient toxicities and deficiencies associated with extreme soil pH are eliminated. In lowland soils the most limiting nutrient is normally nitrogen, and fertilizer nitrogen losses are usually high due to ammonia volatilization, denitrification, and leaching. Nitrogen recovery efficiency in lowland as well as upland rice is usually less than 50%. To improve N recovery efficiency, the crop demand for N and its supply from fertilizers must be synchronized through proper rate, timing, and placement. In upland soils, phosphorus is often the most limiting nutrient, especially in acid soils. Both plant and soil analyses are used to detect and correct nutrient deficiencies and toxicities. To produce 1 metric ton of rice, it is necessary to accumulate approximately 20 kg N, 4 kg P, and 25 kg K in the grain and straw. Since straw is often removed or burned, larger amounts of nutrients, especially N and K, are lost. Thus, fertilizers or manures are normally required to maintain soil fertility.

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10 Corn

10.1 INTRODUCTION

Corn (*Zea mays* L.), known in much of the world as maize, is the world's third most important cereal after wheat and rice. Corn is grown primarily for grain and secondarily for fodder and raw material for industrial processes. The grain is used for both human and animal consumption. The vegetative parts of the plant are cut green and either dried or made into silage for animal feed. The domestication and selection of corn probably began in central or southwestern Mexico about 7000 years ago (Goodman, 1988). The date of origin for cultivated maize in the highlands of central Mexico is unknown, but Palomero Toluqueño was considered an ancient indigenous race by Wellhausen et al. (1952). Kato (1984) proposed a multicenter domestication of maize, with two of the four centers in central Mexico. Highland maize probably came from the higher altitude centers. Excavations at Teotihuacán, in the Valley of Mexico, have uncovered ears with the characteristics of Cónico (Wellhausen et al., 1952), indicating that maize, similar to current types, was important for the ancient civilizations of highland Mexico and has been cultivated at altitudes above 2000 m for millennia (Eagles and Lothrop, 1994). The distinguishable groups of cultivars arose in Mexico and Central America, in the northeastern United States, on the northern coast of South America, in the Andes, and in central Brazil. The Spanish and Portuguese quickly distributed corn throughout the world in the sixteenth century (Jones, 1985). It is now grown in more countries than any other cereal and has produced the largest grain yield of any cereal.

In the early 1990s, more than 50% of the total world area planted with corn was in Latin America, Africa, and Asia, but probably less than 35% of the total world grain corn production was in these areas (Russell, 1991). Except for a few countries in these three continents, average yields per hectare are very low. The chief corn-producing countries are the United States, Russia, Romania, Yugoslavia, Hungary, Italy, China, Brazil, Mexico, South Africa, Argentina, India, and Indonesia. The main reason for its wide distribution is that corn has many assets. These include its high yield per unit of labor and per unit of area. It is a compact, easily transportable source of nutrition. Its husks give protection from birds and rain. It can be harvested over a long period, stores well, and can even be left dried in the field until harvesting is convenient. The grain of corn has been traditionally used for direct human consumption, but at present, the major use of corn is as animal feed. In the United States, approximately 75% of the grain is used as an animal feed and 20% as a source of industrial products (Tollenaar and Dwyer, 1998). It provides numerous useful food products, and it is frequently preferred to sorghum and the millets (Jones, 1985). Thomison et al. (2003) and Tanaka and Maddonni (2008) reported that in feed rations of livestock and poultry, grain with high oil concentration is preferred because of its energy value and as a substitute for animal fats. The chemical composition of corn grain is about 77% starch, 2% sugar, 9% protein, 5% fat, 5% pentosan, and 2% ash (Purseglove, 1985; Maddonni and Otegui, 2006).

The use of transgenic corn hybrids is a new technology adopted in many corn-growing countries in the last decade of the twentieth century and use of this technology is increasing in recent years. Since 1996, several seed companies have commercialized new transgenic corn hybrids resistant to European corn borer (ECB) and lodge less, creating interest among growers and seed companies in their yield response to increasing plant population (Seydou et al., 2000; Stanger and Lauer, 2006). These new hybrids, commonly known as Bt corn, have been genetically engineered to incorporate genes of Bt (Koziel et al., 1993; Armstrong et al., 1995), a toxin effective against larva from both first and second ECB generations (Stanger and Lauer, 2006). Resistance to second-generation ECB

will reduce stalk lodging, which may result in higher maximum yield plant population (Stanger and Lauer, 2006). Lauer and Wedberg (1999) reported that yield of Bt hybrids was 10% higher compared with isoline hybrids. Similarly, Graeber et al. (1999), Seydou et al. (2000), and Stanger and Lauer (2006) compared Bt hybrids to non-Bt hybrids and concluded that the Bt hybrids reduced or eliminated first- and second-generation damage caused by ECB, yielded 4%–6.6% greater than non-Bt hybrids, had decreased stalk lodging and greater test weight. Aflatoxin, produced by the fungus *Aspergillus flavus*, reduces the value of corn and is usually associated with high temperatures, water stress, and insect damage. The U.S. Food and Drug Administration limits corn grain sale with an aflatoxin contamination of 20 ng g^{-1} (Park and Liang, 1993). Wiatrak et al. (2005) reported that Bt hybrids had less aflatoxin when compared with non-Bt hybrids.

10.2 CLIMATE AND SOIL REQUIREMENTS

Corn, with its large number of cultivars of different maturity periods, can be grown over a wide environmental range. It is essentially a crop of warm countries with adequate moisture. The bulk of the crop is grown in the warmer parts of the temperate regions and in the humid subtropics. It is mainly grown from 50°N to 40°S and from sea level to 4000 m in the Andes and Mexico. The water balance of a crop is determined by evapotranspiration (ET), rainfall, and soil characteristics. Reported values for seasonal ET of corn vary widely (440–1000 mm) and are influenced by available water and local environmental parameters (Musick and Dusek, 1980; Eck, 1984). Water deficits reduce crop yields. Rainfall during the corn-growing period should be in the range of 460–600 mm in the temperate regions, and in the tropics, corn does best with 600–900 mm of rain during the growing season.

The deficiency of water during any growth stage of corn can reduce grain yield. However, the magnitude of the reduction depends on the growth stage of the crop at the time of stress, the severity and duration of the stress, and the susceptibility of the genotype to stress (Lorens et al., 1987). Water stress during vegetative development reduces the expansion of leaves, stems, and roots and ultimately affects the development of reproductive organs and potential grain yield (Denmead and Shaw, 1960). It is generally reported that corn is most sensitive to drought stress during pollination, when the delayed emergence of silks may reduce fertilization and subsequent grain yield as a result of fewer seed numbers (Herrero and Johnson, 1981). Drought stress as late as 2–3 weeks following 50% silking may also reduce seed number (Frey, 1981). Drought during the linear growth phase of kernel development primarily affects mean kernel weight by reducing the assimilate production or duration of grain fill, or by a combination of both factors (Jones and Simmons, 1983). Kernels at the tip of the ear often develop poorly when water stress occurs during the seed-filling period (Tollenaar and Daynard, 1978).

In conclusion, maize grain yield is particularly sensitive to water deficits that coincide with the tasseling–silking period and approximately 2 weeks after silking (Otegui et al., 1995). The number of kernels per plant is defined during this period. Oliveira et al. (1993) studied ET and water extraction from different soil depths on a red–yellow podzolic soil, Barreiros-Bahia, Brazil. The accumulated ET during the 95 day crop growth was 455 mm. The period of crop maximum demand 8.02 mm per day took place at 81 days' growth (Oliveira et al., 1993). Water extraction by 0–20 cm, 20–40 cm, 40–60 cm, and 60–80 cm soil depth was 36%, 39%, 22%, and 3%, respectively.

Soil temperatures of 26°C–30°C are optimum for both germination and early seedling growth. Modi and Asanzi (2008) reported that seed germination and vigor increased when growth temperature was increased from 22/16°C to 27/21°C (day/night), but they decreased in response to high temperature (33/27°C). Emergence is normally reduced below 13°C and fails below 10°C (Riley, 1981). Optimum temperature at tasseling is 21°C–30°C. High temperature promotes respiration. Chang (1981) reported that the average respiration loss is about 25% of the photosynthetic rate in the temperate zone and about 35% in the tropics. However, an important effect of temperature is that high temperature, particularly at night, shortens the grain-filling period, thereby reducing the yield (Wilson et al., 1973; Jones et al., 1981). High temperature increases the rate of grain filling

TABLE 10.1
Adequate Soil Chemical Properties for Maximum Corn Grain Yield Grown on a Brazilian Oxisol

Soil Chemical Property	Adequate Value for Maximum Grain Yield	R^2
Base saturation (%)	60	0.4921**
pH in H_2O	6.4	0.7064**
Ca ($cmol_c\ kg^{-1}$)	3.3	0.7344**
Mg ($cmol_c\ kg^{-1}$)	1.4	0.8102**
Ca/Mg ratio	2.4	0.7315**
Ca/K ratio	16.0	0.7837**
Mg/K ratio	7.8	0.9339**
Ca saturation (%)	43	0.7260**
Mg saturation (%)	18	0.8192**
K saturation	2.6	0.7841**

Source: Adapted from Fageria, N.K., *Rev. Bras. Eng. Agric. Amb.*, 5, 416, 2001.

** Significant at the 1% probability level.

but greatly reduces the duration of grain-filling period, whereas low temperatures cause an inverse response (Jones et al., 1981). The work of Hunter et al. (1977) suggests that the grain yield of maize, like that of small grains, is higher at lower temperatures because of an increase in the length of the grain-filling period and greater partitioning of postanthesis dry matter to grain. A detailed description of the climatic requirements of corn is given by Shaw (1977).

Corn can be grown on a wide variety of soils but performs best on well-drained deep loams and silt loams containing adequate organic matter and available nutrients. Corn can be grown on soils with a pH from 5.0 to 8.0, but corn is moderately sensitive to salinity, and 90% relative yield was obtained at an electrical conductivity of about 1.8 dS m^{-1} (Jones, 1985). Soil salinity can have a marked influence on the uptake of a number of nutrients, but decreased dry matter production probably most often results from decreased soil water and increased toxicity of sodium chloride and sulfate in the soil solution (Larson and Hanway, 1977). Adequate soil chemical properties for corn grown on a Brazilian Oxisol are presented in Table 10.1.

10.3 GROWTH AND DEVELOPMENT

Soil moisture, temperature, availability of nutrients, soil, aeration, genotype, and cultural practices influence the development of corn and other crops. Their effects vary substantially throughout the crop's life cycle; therefore, it is important to understand the growth and phenological development of the crop, as well as the relative sensitivities of crop growth stages to environmental stresses. This section provides a brief description of the structure of the corn plant and its phenology.

10.3.1 Germination

The germination of the corn seed is similar to that of many grasses except for scale differences resulting from the relatively large endosperm and embryo of the corn seed (Duncan, 1975). Corn seeds can germinate immediately after maturity, even while attached to the plant. With a favorable environment, the radicle emerges 2–3 days after sowing, and the plumule, enclosed in the coleoptile, breaks through the seed coat 1–2 days later. Other seminal roots, usually three in number,

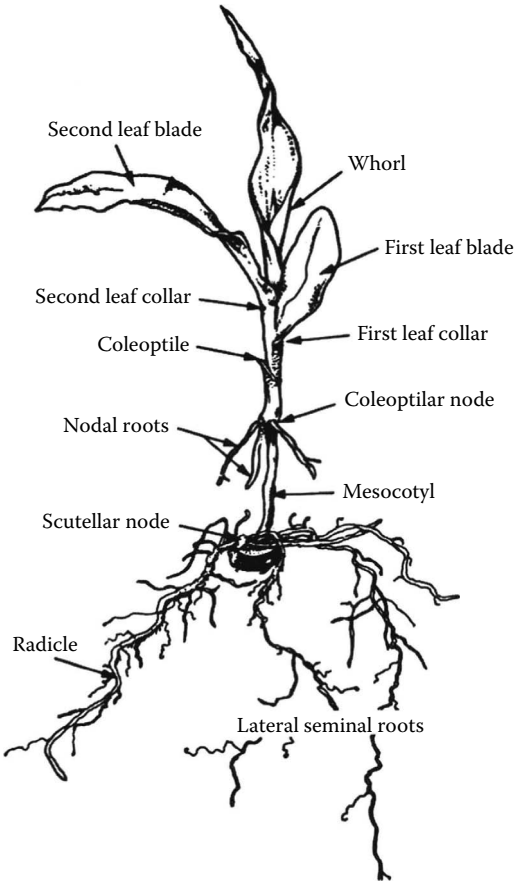

FIGURE 10.1 Morphology of corn seedling. (From Stevens, E.J. et al., *Agron. J.*, 78, 867, 1986. With permission.)

soon follow. The length of the tubular white mesocotyl depends on the depth of planting, and within a few days, it elongates to within 3 cm of the soil surface. In most cultivars, its maximum length is 12.5–15 cm. If the seed is planted deeper than this or growing conditions are unfavorable, elongation stops and the seedling fails to emerge (Purseglove, 1985). Adequate moisture and soil temperatures near 30°C are ideal for germination and plant emergence. The morphology of a corn seedling is shown in Figure 10.1.

10.3.2 Roots

Corn plants initially produce a small seminal root system that is quickly superceded by a large fibrous root system originating from the lower nodes of the stem. The radicle grows from the seed to produce the first seminal root, after which three or more seminal roots grow out sideways from the embryo. They supply most of the nutrition during the first 2 weeks after germination and remain functional for some time (Purseglove, 1985). The seminal roots quickly lose their importance, and the young plant is supported and nourished by the permanent nodal root system. The main root system continues to grow downward and to branch, and additional roots are produced in successive whorls from stem nodes above the crown. According to Anderson (1987), the most rapid root development in corn occurs in the first 8 weeks after planting. In deep soils, the depth of the root system increases linearly with time until tasseling, when it normally reaches it maximum depth. From tasseling to the start of grain filling, stout brace roots develop from nodes near the base of

the stem, growing into the surface soil to support the stem (Larson and Hanway, 1977). During the rapid grain-filling storage, total root length and root dry weight do not increase and may decrease before grain matures (Mengel and Barber, 1974). Root system growth and configuration respond to soil water, temperature, air, nutrient, toxic chemicals, and soil resistance. Management practices can affect root system development by modifying these factors.

10.3.3 Stem and Leaves

Most corn hybrids are about 2.5–3.5 m tall, inbreds and sweet corn cultivars are smaller, plant height tends to increase with increasing relative maturity (Tollenaar and Dwyer, 1998). The corn stem consists of leaf blades, leaf sheaths, nodes, and internodes. Leaves are borne alternately on either side of the stem at the nodes. Each corn leaf consists of a thin, flat blade with a definite midrib and a thicker, more rigid sheath with a smaller midrib. Leaf inclination varies considerably among genotypes, from almost horizontal to almost vertical in one mutant with no collar separating the sheath and blade (Duncan, 1975). The number of leaves per plant varies from seven for some short season open pollinated varieties to more than 30 for some tropical cultivars, leaf number for temperate climate hybrids ranges from 16 to 23 (Tollenaar and Dwyer, 1998).

10.3.4 Inflorescence

The corn plant is monoecious and diclinous, with male and female inflorescences borne in separate inflorescences on the same plant. The male inflorescence is called the tassel, and the female inflorescence is called the ear. The ear is actually a modified spike produced from a short lateral branch in the axil of one of the largest foliage leaves, about halfway down the stem (Purseglove, 1985). Thus, unlike other major cereals, corn produces its economic yield (grain) on a lateral shoot. Because of this separation of ear and tassel, plus the protandry of flowering, corn is primarily a cross-pollinated species.

The pistil of the female flower, known as the silk, develops from the growing point of the flower. It elongates through the length of the husks propelled by the growth of an intercalary main stem located at its base. Each silk continues to grow until it is pollinated and fertilization takes place (Duncan, 1975). Modern hybrids usually have one ear per plant, although up to eight ears may have been initiated. Older cultivars, especially when planted at low plant populations, often produce two ears per plant (Tollenaar and Dwyer, 1998).

10.3.5 Growth Stages

Several methods have been proposed to describe corn growth stages. Larson and Hanway (1977) describe five periods with unique characteristics: (1) planting to emergence, (2) emergence to tasseling, (3) tasseling to silking, (4) silking to physiological maturity, and (5) dry-down period. The classical numerical system proposed by Hanway (1963) has 10 growth stages (Table 10.2). A more detailed approach proposed by Stevens et al. (1986) is given in Tables 10.3 and 10.4. According to Tollenaar and Dwyer (1998), the life cycle of corn can be divided into four distinct phases that are (1) the leaf growth phase, a period of predominantly vegetative growth; (2) the flowering period that includes tassel emergence, anthesis, silking, and fertilization of the florets; (3) the grain filling period in which dry matter is allocated predominantly to the reproductive organs; and (4) the period of grain dry down, a final phase of the life cycle when an impermeable black layer of cells forms at the base of the grain, and no further translocation of carbohydrates to the grain occurs. The duration of each of these phases, the duration of the life cycle is influenced by climatic factors, genotype, and crop management (Tollenaar and Dwyer, 1998). Nitrogen deficiency delays both the vegetative and reproductive stages of phonological development, slightly reduces the leaf emergence rate, and strongly reduces leaf expansion rate and leaf area duration (Uhart and Andrade, 1995).

TABLE 10.2
Definitions of Growth Stages for Maize

Growth Stage	Maize
0	Emergence, coleoptile visible at soil surface
1	Collar of 4th leaf visible
2	Collar of 8th leaf visible
3	Collar of 12th leaf visible
4	Collar of 16th leaf visible. Tips of many tassels visible
5	75% of plants have silks visible
6	Kernels in "blister" stage
7	Very late "roasting ear" stage
8	Early dent stage
9	Full dent stage
10	Physiological maturity

Source: Hanway, J.J., *Agron. J.*, 55, 487, 1963. With permission.

TABLE 10.3
A Field Guide to Pretassel Phenology of Corn

Analog	Stage
0.00–0.90	*Planting to emergence*. By definition, planting was analogous with stage 0.0, emergence of the coleoptile from the soil with stage 0.5, and exposure of the ligule of the first leaf with stage 1.0. Substages 0.0–0.5 were identified according to the terminal location of the coleoptile relative to the surface of the soil. The scutellar node and mesocotyl or scutellar internode were assigned a value of 0.25, while the coleoptilar node and internode were assigned a value of 0.5.
1.00–10.0	*Leaf and tassel emergence*. A leaf was considered fully emerged when the collar and auricles were completely visible. Nodes, internodes, and leaves were numbered sequentially from the first leaf (Figure 10.1). For example, a complete description of a corn plant in which the collar and auricles of the sixth leaf were located halfway along the sheath of the fifth leaf, the most recent fully emerged leaf (i.e., collar and auricles were visible above the auricles of the preceding leaf), would be: phase pretassel, stage five-leaf, substage 0.5. Substages were, therefore, determined from the position of the collar and auricles of the emerging leaf (indicator leaf plus one) relative to the total length of the sheath of the most recently emerged leaf. As plants developed and lower leaves were lost, elongation of the fourth, fifth, sixth, and seventh internodes provided a basis for determining leaf stage and substage. Leaf number was determined by counting internodes, starting at the first internode, to equal or exceed 2.0 cm in length. This was internode 5.0 in field corn and 6.0 in popcorn.
10.00	*Tassel emergence* (*complete*). Documented as though it were an additional leaf according to the relative position of basal tassel branches with respect to the collar and auricles of the last (flag) leaf. The tassel was considered to be fully emerged when the lower branches were entirely visible beyond the collar and auricles of the flag leaf.

Source: Stevens, E.J. et al., *Agron. J.*, 78, 867, 1986. With permission.

10.3.6 Dry Matter Production

Corn uses the C_4 photosynthetic pathway. As a result, it exhibits high leaf photosynthetic rates, low CO_2 compensation points, and the absence of photosynthetic saturation up to full sunlight. Thus, its photosynthetic metabolism differs from that of rice and wheat, the two other major cereals (Hatch and Slack, 1970). Mock and Pearce (1975) reported that the photosynthetic rates of corn, sorghum,

TABLE 10.4
A Field Guide to Post-Tassel Phenology of Corn

Analog	Stage
10.25 10.375(mid) 10.50(late)	*Anthesis early*. Documented according to the proportion of a fertile tassel bearing fully emerged anthers actively shedding pollen. Characteristically, pollen shed began at the midpoint of the central axis and progressed acropetally (upward), then basipetally (downward), followed by the lateral branches. The adaxial floret of each spikelet shed pollen prior to the abaxial floret. The development of male and female reproductive organs was not always synchronized on the same plant; however, under normal conditions with commercial material, silking coincided with 75%–100% of the tassel actively shedding pollen. Three substages, early (25%), mid (50%), and late (75%), were recognized as equal divisions.
10.50 10.625(mid) 10.75(late)	*Fertilization (early)*. Documented according to the proportion of silks on the primary ear that had stopped elongating and had begun to turn brown. Three substages, early (25%), mid (50%), and late (75%), were recognized as equal divisions.
10.50 10.825(mid) 11.00(late)	*Brown silk (early)*. Documented according to the proportion of silks on the primary ear that had turned dark brown. By this stage, pollen shed and fertilization had been completed and the endosperm was a beginning to develop rapidly. Three substages, early (25%), mid (50%), and late (75%), were recognized as equal divisions.
11.00 11.25(mid) 11.50(late)	*Blister (early)*. Kernels appeared as white translucent grains. The endosperm and abundant inner fluid were clear in color, and the embryo was visible on dissection. Three substages, early, mid, and late, were recognized as equal divisions.
11.50	*Milk (early)*. Association with increasing viscosity of the endosperm to resemble a milklike substance. Three substages, early, mid, and late, were recognized as equal divisions.
12.00 12.25(mid) 12.50(late)	*Soft-dough (early)*. Increasing deposits of starch within the endosperm of dent corn caused it to develop a heavy doughlike consistency, and foliar detail was evident macroscopically in the embryo. In popcorn, deposits of vitreous or dense horny endosperm gave the impression of a small lens or incomplete cap to the kernel. A reliable indicator of this stage in popcorn involved crushing kernels to locate vitreous starch deposits. Three substages, early, mid, and late, were recognized as equal divisions.
12.50	*Twenty-five percent solids*. Kernels within the basal third of the dent corn ear by this stage had begun to form dents. In popcorn, glazing or capping of kernels was usually evident near the butt of the ear.
13.00	*Fifty percent solids*. Apparent in both dent and popcorn when the endosperm within a majority of kernels displayed definite signs of hardening to a point adjacent to the distal location of the embryo. By this stage, the husk covering the ear had begun to dry rapidly. Denting or capping (glazing) of the kernels (depending on grain type) was usually evident by this stage under normal climatic conditions, unless the crop was planted abnormally late in the growing season.
13.50	*Seventy-five percent solids*. By this stage, with normal climatic conditions and planting dates, a distinct brown coloration, often more prevalent in popcorn, had begun to develop within the placental regions of kernels. The embryo was noted to be close to fully developed.
14.00	*One-hundred percent solids*. With normal climatic conditions and planting dates and in the absence of additional stress factors, this stage was determined as a point of maximum grain dry matter accumulation and assumed to coincide generally with physiological maturity.

Source: Stevens, E.J. et al., *Agron. J.*, 78, 867, 1986. With permission.

sugarcane, and bermudagrass can reach 60 mg CO_2 dm^{-2} h^{-1}, almost double that of soybean, cotton, and alfalfa, which use the C_3 photosynthetic pathway.

In the modern short-season corn hybrids, approximately 50% of the total seasonal dry matter is accumulated by flowering, with the remaining 50% accumulated during grain-filling period (Tollenaar et al., 2004). In addition, in modern hybrids, about 50% of the dry matter is allocated to the grain and remaining to the straw (Tollenaar et al., 2004). Almost all of the dry matter allocated to the grain is fixed during the grain-filling period and there is little or no remobilization of dry matter accumulated earlier in the plant (Cliquet et al., 1990; Lee and Tollenaar, 2007). Dry

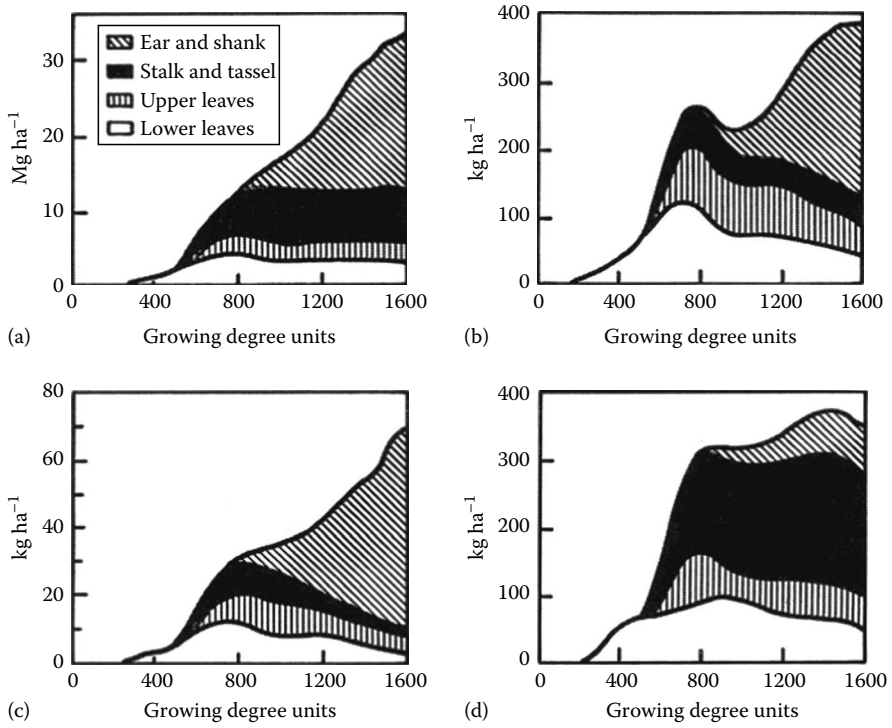

FIGURE 10.2 Aerial dry matter, N, P, and K accumulation in different parts of corn plant yielding 19.3 Mg ha^{-1} of grain. (a) Aerial dry matter accumulation. (b) Aerial N accumulation. (c) Aerial P accumulation. (d) Aerial K accumulation. (From Karlen, D.L. et al., *Agron. J.*, 80, 232, 1988. With permission.)

matter accumulation for corn grown under good management in South Carolina was described by Karlen et al. (1988) and is shown in Figure 10.2. Total shoot dry matter at physiological maturity was 31.8 Mg ha^{-1}, including 16.3 Mg ha^{-1} of grain dry matter. This resulted in a grain/stover ratio of 0.51, excluding root biomass. Leaves accounted for 18% of the aerial biomass at physiological maturity, with 2.8 Mg ha^{-1} of leaves retained both below and above the ear (Figure 10.2). Maximum accumulation in the stalk and tassel was 6.5 Mg ha^{-1} or 20% of the aerial biomass. The nongrain portions of the ear and shank, which were calculated by subtracting grain yield from the ear and shank biomass at physiological maturity, accounted for 3.4 Mg ha^{-1} or approximately 11% of the aerial dry matter. Hanway (1962a) reported a similar dry matter accumulation pattern in corn under field conditions. A farmer in Illinois consistently obtained grain yields ranging between 15 and 20 Mg ha^{-1}, which corresponds to total above ground dry matter accumulation of 30–40 Mg ha^{-1} (Tollenaar and Dwyer, 1998). Similar yields had been previously reported by a farmer in Michigan (Tollenaar, 1983).

According to Karlen et al. (1988), daily dry matter growth rates show two distinct peaks. The first occurs during vegetative growth when the potential ovule number is being established. During this period, maximum rates of dry matter accumulation for lower leaves, upper leaves, and stalk and tassel fractions were approximately 100, 200, and 300 kg ha^{-1} day^{-1}, respectively. The second peak, which occurs during grain fill, shows a peak growth rate of approximately 450 kg ha^{-1} day^{-1}, which goes directly into the ear and shank. Improvement in grain harvest index has been an important strategy in improving crop yields in the last several decades. In addition, delay in leaf senescence and the extended duration of the grain-filling period are important breeding goals aimed at increasing grain yields (Tollenaar and Dwyer, 1998).

10.3.7 Leaf Area Index

Green leaf area, usually expressed as (m^2 leaf surface m^{-2} land area) or leaf area index (LAI), is a major factor determining solar radiation interception, canopy photosynthesis, and, therefore, yield (Valentinuz and Tollenaar, 2006). Duncan (1975) stated that the interception of light is the primary function of corn canopies, but the intercepted light should be used efficiently, and this is a function of leaf angle. He pointed out that between LAI values of 3 and 4, horizontal leaves intercept about 90% of the light, while leaves 15° from vertical intercept only 75%–80%. The development of a corn canopy capable of intercepting almost all photosynthetically active radiation by silking requires a plant density of 5–10 plants per m^2, depending on the cultivar and row spacing.

Hoyt and Bradfield (1962) reported that the net assimilation rate (rate of growth per unit leaf area) of corn is constant when LAI is less than 2.7 but declines rapidly as LAI increases above that value. Eik and Hanway (1966) also reported a linear relationship between corn grain yield and LAI up to an LAI of 3.3 at midsilk. Leaf growth continues until silking, or soon after (Hanway, 1962a), and there is considerable evidence that grain yields and grain number increase with LAI up to values ranging from approximately 3 to 5 for both the U.S. Corn Belt (Eik and Hanway, 1966) and tropical conditions (Yamaguchi, 1974).

The LAI of corn increases in a sigmoid fashion from the seedling to the silking growth stage, decreases slightly during grain filling, then declines rapidly toward the end of the crop cycle (Tollenaar and Dwyer, 1998). Major factors that influence LAI are genotypes, management practices, and environmental conditions. The LAI is smaller for inbreds compared to hybrids and larger for long-cycle hybrids compared to short-cycle hybrids (Tollenaar and Dwyer, 1998). The decrease in LAI during grain filling may be associated with leaf senescence, and the rate of leaf senescence varies among hybrids. Modern hybrids stay green longer than older hybrids (Tollenaar and Aguilera, 1992; Tollenaar and Dwyer, 1998).

10.4 YIELD AND YIELD COMPONENTS

The average grain yields of corn vary substantially among the temperate, subtropical, and tropical regions. In the early 1970s, it was estimated that average corn yields in the temperate, subtropical, and tropical regions were 3.5, 1.8, and 1 Mg ha^{-1}, respectively (Goldsworthy, 1974).

In temperate regions, a maximum yield of 22 Mg ha^{-1} has been reported in Michigan, and yields of 10 Mg ha^{-1} at the commercial level are common (Fischer and Palmer, 1983). Tollenaar and Lee (2002) and Johnson et al. (2006) reported that corn has an estimated genetic yield potential of 25 Mg ha^{-1}. In the tropics, most of the high yields reported are confined to intermediate- or high-altitude areas having long rainy seasons. The yields of 12 Mg ha^{-1} have been reported from experiments in Salisbury, Zimbabwe (latitude 18°S, altitude 1500 m), and yields of 10 Mg ha^{-1} have been reported from Kitale, Kenya (latitude 2°N, altitude 1890 m) (Fischer and Palmer, 1983). Average yields in several well-managed, irrigated field experiments conducted on Oxisols in Hawaii, Brazil, and Puerto Rico were 7.6–9.5 Mg ha^{-1} with maximum yields of almost 12 Mg ha^{-1} (Tsuji, 1985). In the lowland tropics, experimental yields typically range from 5 to 8 Mg ha^{-1} with good management practices. Differences among experimental yields probably reflect the effects of temperature, solar radiation, rainfall, and agronomic practices. Low grain yields of most tropical corn cultivars have also been attributed to the poor partitioning of total dry matter to the grain (Goldsworthy, 1974; Yamaguchi, 1974).

The yield of corn is the product of kernel number per unit area and kernel weight (Bolanos and Edmeades, 1996; Pagano and Maddonni, 2007). Kernel number is positively related to crop growth around silking and biomass allocation to reproductive organs (Echarte et al., 2004). Among cultural practices, plant population density has the greatest positive impact on crop growth rate around silking, which is reflected in kernel number and grain yield (Maddonni et al., 2001, 2006). For a particular cultivar, grain weight is generally more stable than grain number, and large differences

in yield due to environmental conditions are usually the result of fluctuations in grain number. The variation in grain yield of 12 tropical populations, grown at 15 sites in Mexico to provide different environments and planting dates, was linearly related to change in grain number ($Y = 482.4 + 13.6X$, $R^2 = 0.70$) and rate of grain growth ($Y = 310 + 959X$, $R^2 = 0.36$) but not to duration of grain growth (Fischer and Palmer, 1983). Grain number per unit area depends on events before and around flowering. Deficiency of N, moisture stress, and inadequate radiation at that time significantly reduce grain number.

Large differences exist between potential experimental yields and yields obtained by farmers. The difference is particularly great in developing countries, where corn is grown by subsistence farmers without access to improved management techniques. There are many reasons for low yields, including drought and nutrient stresses, inadequate pest control, and use of poorly adapted cultivars with low yield potential. Dramatic yield increases in developing countries will probably require the simultaneous improvement of crop management and germplasm. Fischer and Palmer (1984) suggested the following measures to improve corn germplasm for tropical environments:

1. There is variation in the rate and percentage of germination of seeds at both warm and cool soil temperatures, which suggests that it should be possible to develop, through recurrent selection, genotypes that will germinate and grow at a wide range of temperatures (Hardacre and Eagles, 1980).
2. Increasing the duration of growth and the fraction of the total duration devoted to grain filling may provide other opportunities to increase yield.
3. The rate of dry matter production during ear development is critical for yield determination. It is often possible to increase growth rates by improving light interception with higher plant populations. The rate of growth per unit of intercepted light might also be increased by selection for the high rates of photosynthesis or by the modification of the canopy structure through changes in leaf angle, leaf size, and the vertical distribution of leaves.
4. Selection for shorter plants, with uniform plant height, fewer and narrower leaves, and a small tassel has resulted in a shorter interval between pollen shed and silking and fewer barren plants at dense plant populations.
5. Tolerance to high plant populations is also associated with the production of more than one ear at lower plant populations.

Maize yields in the United States have steadily increased since 1930, and genetic improvement has been credited with over 50% of the increase (Russell, 1991). Recently, Lee and Tollenaar (2007) reported that commercial grain yield of corn in the United States increased from about 1300 kg ha^{-1} in 1939 to 7800 kg ha^{-1} in 2005, about 99 kg ha^{-1} per year, with similar gains (88 kg ha^{-1} per year) observed in Canada during the hybrid era (1939–present). Improvement in agronomic practices also contributed to increased yields. Among improved agronomic practices, increases in plant densities and the use of higher rates of N fertilizer have probably been the most important. For example, increasing N fertility has multiple beneficial effects, including increased LAI, leaf area duration, crop photosynthetic rate, and radiation use efficiency (Sinclair and Horie, 1989; Connor et al., 1993).

Current commercial plant densities in North America are in the range of 75,000–80,000 plants ha^{-1} under favorable environmental conditions (Lee and Tollenaar, 2007). Shapiro and Wortmann (2006) reported that decreasing row spacing from 0.76 to 0.51 m resulted in a 4% increase in grain yield. Crop nitrogen demand also increases as plant density increases (Penning de Varies et al., 1993). Tollenaar and Lee (2002) reported that improvement in the corn yield was due to interaction between genetics and agronomic practices. Publicly and privately funded breeding programs have contributed to this improvement of maize yields, with publicly funded programs emphasizing the genetic improvement of populations and privately funded programs focusing on F_2 and backcross populations. Long-term population improvement programs provide improved germplasm sources and inbreds for breeding programs that emphasize short-term breeding objectives (Fountain and Hallauer, 1996).

10.5 NUTRIENT REQUIREMENTS

Achieving high corn yields requires an adequate supply and balance of essential nutrients. The addition of plant nutrients as fertilizers is effective only if they are absorbed and used for the production of increased yield (Barber and Olson, 1968; Shapiro and Wortmann, 2006; Barbieri et al., 2008). Further, the quantity of nutrients required by a crop depends on soil, climate, yield level, cultivar planted, and management practices. Fertilizer needs can be assessed by soil and plant analysis as well as by visual deficiency symptoms. A detailed description of these nutritional diagnostic techniques is given in Chapter 4. In this section, nutrient removal by the corn crop and nutrient concentrations in plant tissues are discussed.

Nutrient accumulation and plant concentrations vary among agroecosystems, but these values can serve as guides for assessing the nutritional requirements and status of the corn crop. Actual fertilizer recommendations should be made on the basis of experimental results obtained for different nutrients and specific agroclimatic regions. One approach to reduce the impact of nutrient deficiency on maize production may be to select cultivars that more effectively absorb and utilize available nutrients for grain production (Lafitte and Edmeades, 1994). The grain yields of newer corn hybrids are greater than those of older hybrids at different levels of N fertility (Ding et al., 2005; Echarte et al., 2008). Differences among older and newer corn hybrids have been associated, in general, with increased stress tolerance, higher rates of dry matter accumulation during the grain-filling period (Tollenaar and Wu, 1999), and reduced rates of visible leaf senescence (Valentinuz and Tollenaar, 2004). Ding et al. (2005) and Echarte et al. (2008) reported that the increase in dry matter accumulation due to increased N fertility was due to higher sustained carbon exchange rates (CER) and chlorophyll content during the grain-filling period. This response to higher N fertility was consistent for both older and newer hybrids.

Nitrogen is one of the most important nutrients limiting maize yield and quality in various parts of the world (Miao et al., 2007). Accurate fertilizer N recommendations for corn production are important for maximizing productivity and profit while minimizing the environmental impacts of fertilizer use (Delin, 2004; Miao et al., 2007). Nitrogen fertilizer requirements depend on many factors, including yield goal, inorganic soil N, potential N mineralization, soil type, and numerous environmental factors (Schlegel and Havlin, 1995). Maximizing the quantity of fertilizer N recovered by the crop, or minimizing the quantity of residual fertilizer N after harvest, generally will reduce potential groundwater contamination (Keeney, 1987). Apparent fertilizer N recovery (AFNR) generally ranges between 30% and 70% (Legg and Meisinger, 1982), and depends on many factors, including location or soil type, inorganic soil N content, N rate, and other N or water management factors (Walters and Malzer, 1990). Generally, AFNR decreases with increasing N rate (Oberle and Keeney, 1990b). AFNR may be higher in coarse-textured soils than in fine-textured soils because of greater N mineralization in the fine-textured soils. The use of adequate fertilizer N level is one way to get maximum yield while improving N recovery efficiency.

Fertilizer N rates required for maximum or optimum yield varies widely between locations (or soils) and years (Onken et al., 1985). In long-term studies with corn, the N rate required for maximum yield varied from 174 to 241 kg N ha^{-1} on several rainfed silt loam Wisconsin soils, compared with 185–258 kg N ha^{-1} on irrigated sandy loam and loamy sand soils (Oberle and Keeney, 1990a). Fertilizer N recommendations for irrigated corn in western and south central Nebraska varied between 56 and 184 kg N ha^{-1} and depended on soil profile and the nitrate-N content of irrigation water (Ferguson et al., 1991). Nitrogen fertilizer recommendations for corn in the Midsouth states (the United States) generally are 26 kg of N per Mg of grain production expected under irrigated conditions (Bruns and Abel, 2003). These recommendations usually call for split application of N fertilizer, with 30%–50% of the total fertilizer being applied at planting (Bruns and Abel, 2003). The remaining of the N should be applied at growth stage V6 as described by Ritchie et al. (1997).

Decisions concerning optimum fertilizer rates usually involve fitting some type of statistical model to yield data collected for several fertilizer rates. Although several different models are

commonly used to describe crop yield response to fertilizers, it is seldom explained why one model is selected over others. Cerrato and Blackmer (1990) evaluated several models (linear-plus-plateau, quadratic-plus-plateau, quadratic, exponential, and square root) commonly used for describing the response of corn (*Zea mays* L.) to N fertilizer (Figure 10.3). The evaluation involved 12 site-years of data, each having 10 rates of N applied preplanting. All models fit the data equally well when evaluated by using the R^2 statistic. All models indicated similar maximum yields, but there were marked discrepancies among models when predicting the economic optimum rates of fertilization. The mean (across all site-years) economic optimum rates of fertilization as indicated by the various models ranged from 128 to 379 kg N ha^{-1} at a common fertilizer-to-corn price ratio. Statistical analyses indicated that the most commonly used model, the quadratic model, did not give a valid description of the yield responses and tended to indicate the optimal rates of fertilization that were too high. The quadratic-plus-plateau model best described the yield responses observed in this study. The results clearly show that, especially amid increasing concerns about the economic and environmental effects of overfertilization, the reason for selecting one model over others deserves more attention than it has received in the past (Cerrato and Blackmer, 1990).

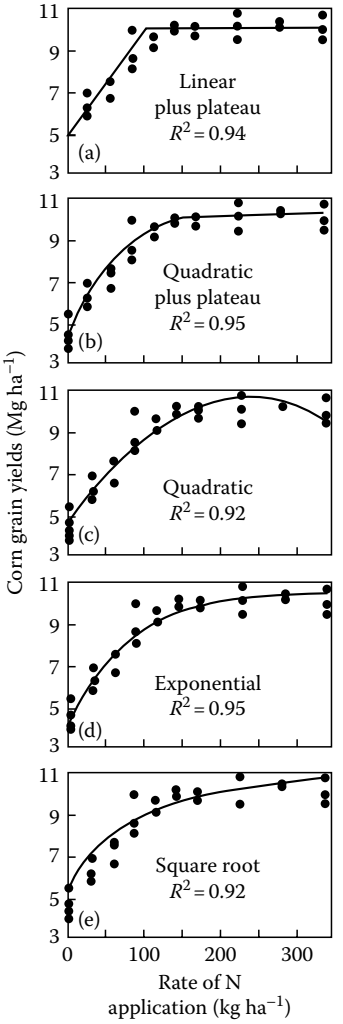

FIGURE 10.3 Relationship between rate of N applied and corn grain yield as a function of five models. (From Cerrato, M.E. and Blackmer, A.M., *Agron. J.*, 82, 138, 1990. With permission.)

Adequate nitrogen rates also depend on whether the crop is grown as a monoculture or in rotation. Figure 10.4 shows that corn grain yield decreased when corn in monoculture was grown for 60 years in central Brazil (Thornton et al., 1995). Cereals and other nonlegumes typically require less fertilizer N when grown in rotation with a legume. Nitrogen credits for a previous legume crop, in combination with other site-specific information, are often used to reduce fertilizer N recommendations (Lory et al., 1995). Lory et al. (1995) reported a positive N rotation effect associated with planting corn following wheat or corn following wheat and alfalfa. That is, for corn grown in rotation, the economic N rate was smaller (by 36 kg N ha^{-1}), and maximum yield was greater than for continuous corn.

Binford et al. (1992) reported that soil testing is an effective tool for improving corn N fertilizer management. Soil NO_3 concentration explained 76% of the variability in relative grain yields (Figure 10.5).

The use of N-efficient genotypes is another strategy of improving corn yields and reducing cost of production. A number of researchers have reported genetic variability in N-use efficiency under both low and high N rates (Work et al., 2007; Fageria, 2009). Efficiency is the ability of a genotype to convert inputs or nutrients into desired outputs or minimize the conversion of inputs into waste (Lynch, 1998). Additionally, N efficiency has been defined as the ability of a genotype to realize an above-average grain yield under conditions of low N availability or suboptimal N supply (Graham, 1984).

Phosphorus deficiency is a principal yield-limiting factor for annual crop production in acid soils of temperate as well as tropical regions. Economic considerations often require the judicious management of P fertilizer inputs to such soils. Fertilizer P recommendations depend on a knowledge of (1) the existing level of available soil P; (2) the optimum level of soil P for the crop to be grown; and (3) the level of fertilizer that must be added to raise available soil P to the optimum level.

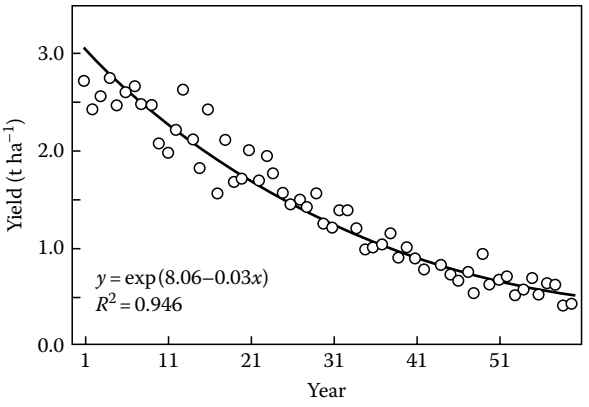

FIGURE 10.4 Corn grain yield as a function of years of cultivation in monoculture in an Oxisol of central Brazil. (From Thornton, P.K. et al., *Agron. J.*, 87, 131, 1995. With permission.)

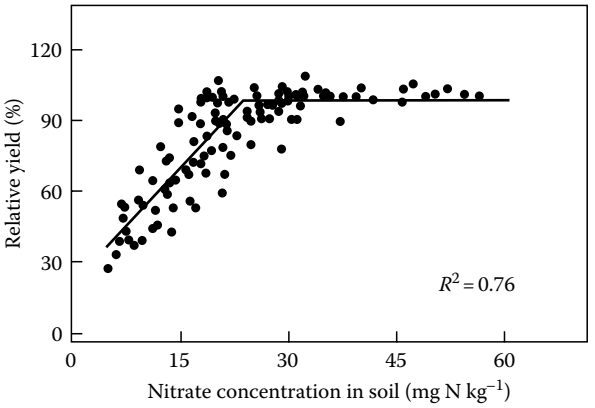

FIGURE 10.5 Relationship between relative yield and NO_3 concentration in soil. (From Binford, G.D. et al., *Agron. J.*, 84, 219, 1992. With permission.)

Figures 10.6 and 10.7 show the critical P level for corn by Mehlich-1 and Bray 1 extractant for an Oxisol in the Brazilian Amazon. Maximum corn yield was achieved at about 6 mg P kg^{-1} by Mehlich-1 and 9 mg kg^{-1} by Bray 1 extracting solution. Cox (1992) determined critical P levels for corn in a Typic Umbraquult soil using Mehlich-3 extracting solution (Figure 10.8). He estimated critical P levels by the linear-plateau and exponential models. For the linear-plateau function, the critical P level ranged from 18 to 33 mg kg^{-1}, with an average of 39. This means that soil P test levels for maximum corn yields varied from soil to soil, from extracting solution used, and in response to the statistical model used for the interpretation of the data.

In the United States, fertilizer P is applied to a majority of corn fields. In the 2001 crop year, for example, the National Agricultural Statistics Service (2002) estimated that 79% of the 607,000 ha of corn fields received P fertilizer applications that averaged 23 kg P ha^{-1} or 53 kg P_2O_5 ha^{-1}. Starter fertilizers with high P analysis are commonly used in the northeastern United States for corn production, despite many soils testing above the optimum level of soil test P (>50 mg P kg^{-1}) Roth et al. (2006). This is because several researchers have reported early growth or yield responses to starter fertilizer on soils with high P soil test levels (Jokela, 1992; Bundy and Andraski, 1999; Roth et al., 2006).

The use of phosphorus-efficient genotypes to increase and/or stabilize crop production has become increasingly attractive in recent years due to the high cost of fertilizer and to pollution problems. The results of a study conducted at the National Rice and Bean Research Center, Goiania,

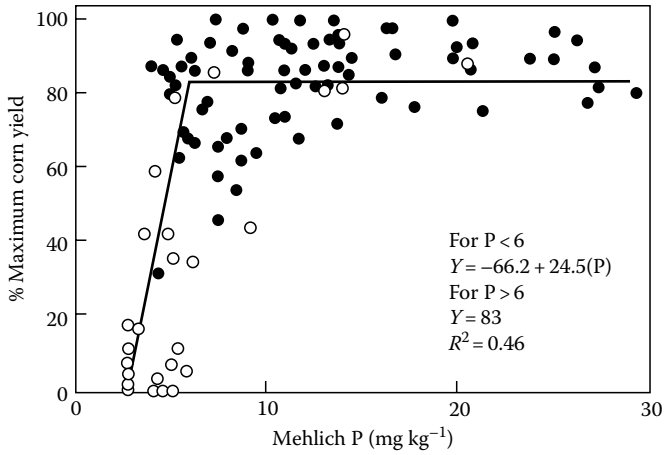

FIGURE 10.6 Relationship between Mehlich-1 extracting soil phosphorus and yield of corn. (From Smith, T.J. and Cravo, M.S., *Agron. J.*, 82, 309, 1990. With permission.)

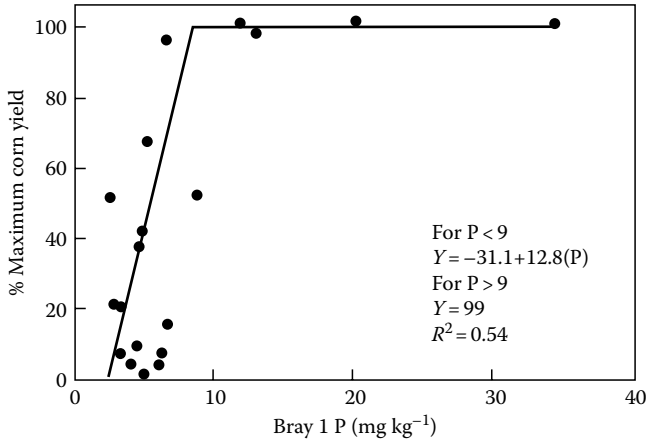

FIGURE 10.7 Relationship between Bray 1 extracting soil phosphorus and yield of corn. (From Smith, T.J. and Cravo, M.S., *Agron. J.*, 82, 309, 1990. With permission.)

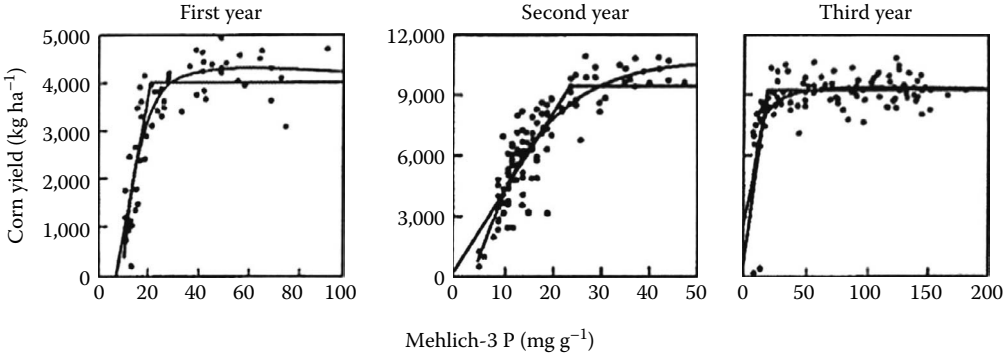

FIGURE 10.8 Response of corn to Mehlich-3 P with linear-plateau and exponential prediction functions for three corn crops. (From Cox, F.R., *Soil Sci. Soc. Am. J.*, 56, 1504, 1992. With permission.)

TABLE 10.5
Phosphorus Uptake in the Shoot and P-Use Efficiency of Nine Corn Genotypes under Different P Levels

	P Uptake in Shoot (mg/pot)				
Genotype	Low P	Medium P	High P	Average	P Use Efficiency (mg/mg) across Medium and High P Levels
1. AG519	1.11bc	7.41ab	11.29ab	6.60b	140ab
2. BR157	0.99c	5.02b	11.37ab	5.79b	123b
3. BR112	1.63a	9.79a	14.05a	8.48a	145ab
4. BR126	0.87c	7.31ab	9.93ab	6.03b	195ab
5. BR451	1.10bc	7.38ab	12.51ab	6.99ab	128ab
6. C701	0.90c	6.18ab	10.59ab	5.88b	130ab
7. C805	1.20abc	7.94ab	12.99ab	7.38ab	140ab
8. Dina 170	0.80c	4.93b	12.01ab	5.90b	197a
9. Sintetico 6	1.53ab	6.77ab	9.18b	5.82b	153ab
F-test	**	**	*	**	**
CV %	15	18	14	18	25

Source: Fageria, N.K. and Baligar, V.C., *J. Plant Nutr.*, 20, 1267, 1997.
Means in the same column followed by the same letter are not significantly different at 0.05 probability level by Tukey's test.

$$\text{P use efficiency} = \frac{\text{Dry matter yield of root and shoot across medium and high P level} - \text{Dry matter yield of root and shoot at low P level}}{\text{P accumulation in root and shoot across medium and high P level} - \text{P accumulation in root and shoot at low P level}}$$

*,** Significant at 0.05 and 0.01 probability levels, respectively.
NS = not significant.

Brazil, showed that corn genotypes differ significantly in their P requirements (Table 10.5). Phosphorus uptake under three P fertilizer levels differed significantly among genotypes. At the low P level, uptake ranged from 0.87 to 1.63 g kg^{-1}; at the medium P level, from 4.93 to 9.79 g kg^{-1}; and at the high P level, from 9.18 to 14.05 g kg^{-1}. Low and high values of P uptake in shoot dry matter are related to dry matter production. P-use efficiency also differed significantly among genotypes across P levels (Table 10.5). Genotype Dina 170 had the highest P-use efficiency, and genotype BR107 had the lowest. Based on dry matter production (root plus shoot) at the low P level and P-use efficiency, the genotypes were classified into four groups (Figure 10.9), according to the methodology proposed by Fageria and Baligar (1993). These groups were as follows:

1. Efficient and responsive: Genotypes that produced dry matter yields higher than the average of 20 genotypes at the low P level and responded well to the addition of P. Genotype Sintetico 6 falls into this category.
2. Efficient and nonresponsive: Genotypes that produced higher than average dry matter yields, but P-use efficiency was lower than the average of nine genotypes. Genotypes BR112, BR451, and C805 fall into this category.
3. Nonefficient and nonresponsive: Genotypes that produced less than average dry matter yields, but P-use efficiency was higher than average. In this group, fall genotypes BR126 and Dina 170.
4. Nonefficient and nonresponsive: Genotypes that produced lower than average dry matter yields as well as lower than average P-use efficiency. In this group fall the genotypes A9519, BR107, and C701.

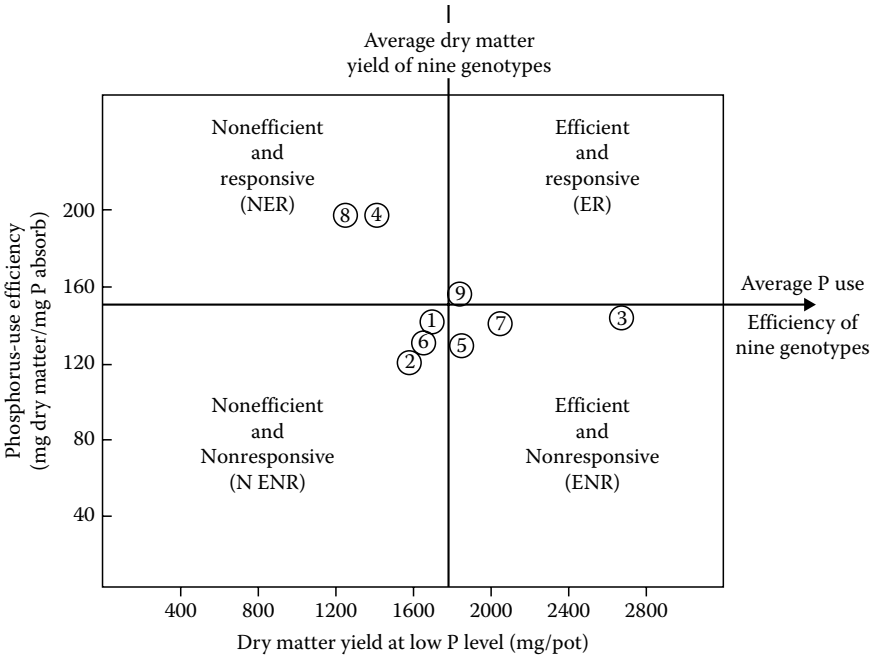

FIGURE 10.9 Classification of nine corn genotypes for phosphorus-use efficiency. Values in the circles refer to genotype numbers, which are numbered in Table 10.5.

From a practical point of view, genotypes that are efficient and responsive are the best. These genotypes can produce well under low-P fertility and respond well to fertilizer P application. The second group, which can produce well under low-P fertility, is efficient and nonresponsive.

Deficiency of K is not as common as nitrogen and phosphorus in the corn-producing areas of the world. However, this nutrient can become deficient if it is removed in large amounts from fields (in grain and stover) without being replaced in fertilizers. Figures 10.10 and 10.11 show the response of corn to extractable K in a humid tropical Ultisol. Critical exchangeable K levels for corn were 110 kg ha^{-1} (55 mg K kg^{-1}) on the loam (Figure 10.10) and 90 kg ha^{-1} (45 mg K kg^{-1}) on the sandy loam Ultisols (Figure 10.11).

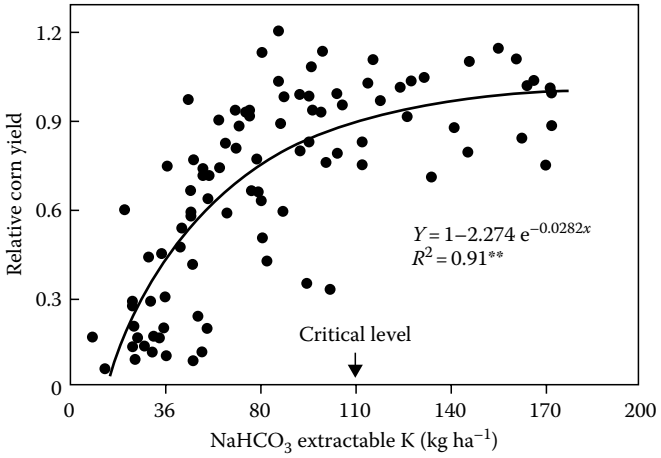

FIGURE 10.10 Relationship between $NaHCO_3$ extractable K and relative corn yield on the loamy soil. (From Cox, F.R. and Uribe, E., *Agron J.*, 84, 480, 1992. With permission.)

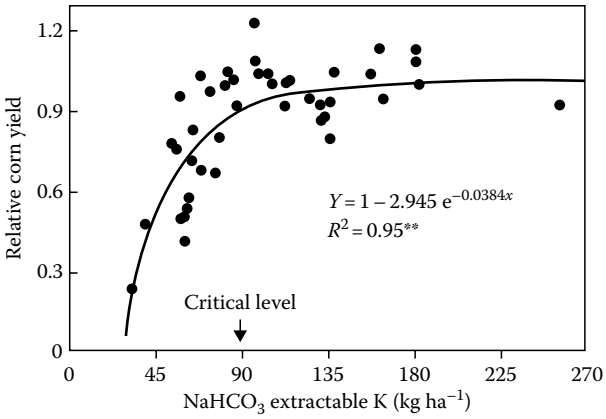

FIGURE 10.11 Relationship between $NaHCO_3$ extractable K and relative corn yield on the sandy loam soil. (From Cox, F.R. and Uribe, E., *Agron J.*, 84, 480, 1992. With permission.)

10.5.1 Nutrient Uptake

Nutrient uptake (concentration × dry matter) is directly related to dry matter production. Hanway (1962b) and Sayre (1955) conducted classical studies on the uptake of N, P, and K by corn crops. In addition, Karlen et al. (1988) conducted more detailed studies of uptake and distribution of N, P, K, Ca, Mg, S, B, Cu, Mn, Fe, and Zn in different plant parts as a function of growing degree units (GDU). These authors calculated accumulated growing degree units with the help of the following equation and used them as a time scale for nutrient accumulation:

$$\text{GDU} = \frac{T_{\min} + T_{\max}}{2} - 10°\text{C} \tag{10.1}$$

where

$T_{\min}$ is the minimum daily temperature or 10°C, whichever is larger
$T_{\max}$ is the maximum daily temperature or 30°C, whichever is smaller

The accumulation of nutrients in different plant parts of corn is presented in Figures 10.12 through 10.14. Total shoot N accumulation was approximately 386 kg ha^{-1} in 32 Mg ha^{-1} dry matter at physiological maturity. Maximum N accumulations in lower leaves (leaves below the ear), upper leaves (leaves above the ear), stem and tassel, and ear and shank were approximately 122, 81, 56, and 255 kg ha^{-1}, respectively. Two distinct features of tissue N contents (Figures 10.12 and 10.13) are the gradual decline in vegetative N during reproductive growth stages and the apparent net loss of shoot N shortly after tassel emergence (900 GDU). The former presumably reflects translocation from vegetative plant parts to the developing grain. The latter may result from volatilization losses because there is no major sink for N-rich compounds between tasseling and the beginning of grain filling. Another mechanism restricting N uptake at this time may be feedback inhibition (Karlen et al., 1988).

At physiological maturity, total shoot P accumulation was approximately 70 kg ha^{-1}; and peak accumulations in lower leaves, upper leaves, stem and tassel, and ear and shank fractions were approximately 13, 10, 9, and 59 kg ha^{-1}, respectively (Figure 10.2). Phosphorus accumulated steadily until maturity, and during grain fill, there was considerable translocation of P from vegetative parts to the grain.

With regard to K, 86% was accumulated by silking, and only 19% of the K was contained in the ear and shank portion. Thus, most of the K absorbed remained in the stover and was recycled through crop residues for future crop production.

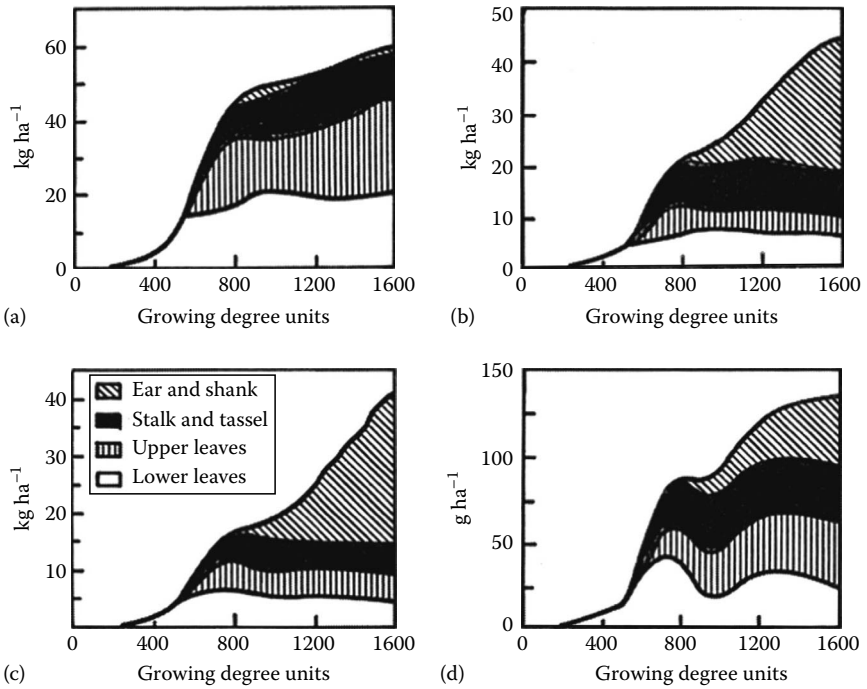

FIGURE 10.12 Accumulation of Ca, Mg, S, and B in different parts of corn plant for corn yielding 19.3 Mg ha^{-1} of grain. (a) Aerial Ca accumulation. (b) Aerial Mg accumulation. (c) Aerial S accumulation. (d) Aerial B accumulation. (From Karlen, D.L. et al., *Agron. J.*, 80, 232, 1988. With permission.)

The accumulation of Ca, Mg, and S continued throughout the growing season. There was essentially no translocation of Ca to the ear during grain fill, but a small amount of Mg was translocated from leaf and stalk fractions to the ear and shank during reproductive growth. In the case of S, approximately 2 kg ha^{-1} was translocated from the lower leaves during early grain fill, but there was essentially no translocation of S from upper leaves or the stalk and tassel fraction.

Plant B content declined during early grain fill in all plant parts; this suggests that uptake slowed, since B does not readily translocate from older tissues to meristematic regions. Increased accumulation during the latter stages of grain fill and nearly uniform distribution at physiological maturity suggest that fertilization programs must provide adequate amounts of B throughout the season (Karlen et al., 1988). There was very little translocation of Cu among the plant fractions, and at physiological maturity, the distribution was 16%, 26%, 14%, and 44% in the lower leaves, upper leaves, stem and tassel, and ear and shank, respectively.

The accumulation of Fe showed two distinct peaks, one near silking and the other approximately halfway through the grain-fill period (Figure 10.13). Iron accumulation was 45%, 21%, 16%, and 18% in lower leaves, upper leaves, stem and tassel, and ear and shank fractions, respectively.

Total manganese accumulation was approximately 0.9 kg ha^{-1}. Plant Mn content increased throughout the growing season, although more than 70% was accumulated by silking. Approximately 18%, 44%, 21%, and 17% was located in the lower leaves, upper leaves, stem and tassel, and ear and shank fractions, respectively, at physiological maturity.

Zinc accumulation (Figure 10.13) totaled approximately 0.8 kg ha^{-1} at physiological maturity, and distribution was 8%, 20%, 16%, and 56% in lower leaves, upper leaves, stem and tassel, and ear and shank, respectively.

In conclusion, the results of Karlen et al. (1988) showed that the total accumulation at physiological maturity was approximately 31,800, 386, 70, 370, 59, 44, 40, 0.13, 0.14, 1.9, 0.9, and 0.8 kg ha^{-1}

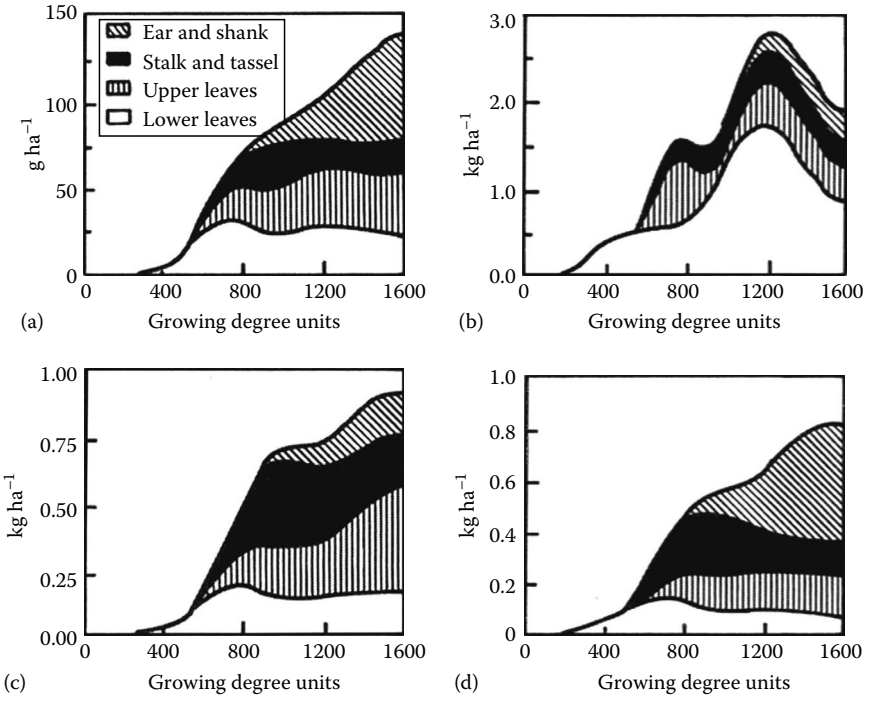

FIGURE 10.13 Accumulation of Cu, Fe, Mn, and Zn in different parts of corn plant for corn yielding 19.3 Mg ha^{-1} of grain. (a) Aerial Cu accumulation. (b) Aerial Fe accumulation. (c) Aerial Mn accumulation. (d) Aerial Zn accumulation. (From Karlen, D.L. et al., *Agron. J.*, 80, 232, 1988. With permission.)

for dry matter, N, P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn, respectively. The amounts of accumulation measured in this study can provide general guidelines for nutrient uptake by high-yielding corn. Fageria (2001) studied nutrient accumulation in corn grown on Brazilian Oxisol throughout the crop growth cycle (Tables 10.6 and 10.7). Macro and micronutrients accumulation significantly increased with increasing plant age. Nutrient accumulation decreased in the following order: N > K > Ca > Mg > P > Mn > Zn > B > Cu. The following percentages of total shoot nutrients were translocated to the

TABLE 10.6
Macronutrients Accumulation in Corn Plants during Crop Growth Cycle

Plant Age in Days	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	Ca (kg ha^{-1})	Mg (kg ha^{-1})
18	1.91	0.13	1.78	0.28	0.13
35	31.39	2.41	33.56	4.54	2.74
53	143.14	10.37	189.84	27.59	15.77
69	147.27	13.50	197.56	37.47	23.18
84	186.40	20.75	237.08	51.78	34.42
119 (straw)	72.03	4.47	152.56	33.41	20.46
119 (grain)	127.42	16.71	34.33	8.22	8.64
Total	199.44	21.19	186.89	41.64	29.10
R^2	0.91**	0.93**	0.88**	0.89**	0.89**

Source: Adapted from Fageria, N.K., *Rev. Bras. Eng. Agric. Amb.*, 5, 416, 2001.
** Significant at the 1% probability level.

TABLE 10.7
Micronutrients Accumulation in Corn Plants during Crop Growth Cycle

Plant Age in Days	Zn (g ha^{-1})	Cu (g ha^{-1})	Mn (g ha^{-1})	Fe (g ha^{-1})	B (g ha^{-1})
18	1.75	0.60	3.63	75.36	0.61
35	28.59	11.74	46.32	811.36	10.80
53	145.52	59.22	295.73	897.99	81.82
69	223.47	69.54	418.05	1513.46	90.22
84	319.81	79.32	700.27	1890.49	133.22
119 (straw)	184.37	53.32	452.16	2048.24	103.12
119 (grain)	192.00	13.75	82.21	205.88	42.62
Total	376.33	67.07	534.36	2254.12	145.75
R^2	0.90**	0.84**	0.85**	0.91**	0.90**

Source: Adapted from Fageria, N.K., *Rev. Bras. Eng. Agric. Amb*., 5, 416, 2001.
** Significant at the 1% probability level.

TABLE 10.8
Nutrient Accumulation in Grain and Straw of Corn Plants to Produce 1 t of Grain

Nutrient	Required to Produce 1 t of Grain
Nitrogen (kg)	24
Phosphorus (kg)	3
Potassium (kg)	23
Calcium (kg)	5
Magnesium (kg)	4
Zinc (g)	46
Copper (g)	8
Manganese (g)	65
Iron (g)	27
Boron (g)	18

Source: Adapted from Fageria, N.K., *Rev. Bras. Eng. Agric. Amb*., 5, 416, 2001.

grain: 64% N, 79% P, 18% K, 20% Ca, 30% Mg, 51% Zn, 21% Cu, 15% Mn 39% Fe, and 29% B. The remaining nutrients were retained in the straw. To produce 1 t of grain, corn plants accumulated macro and micronutrients as shown in the Table 10.8. In northern Colorado, United States, 24 kg of N was required to produce 1 Mg of corn grain. Halvorson and Reule (2006) reported that 29 kg of N was required to produce 1 Mg of corn.

10.5.2 Nutrient Concentration

Plant-based diagnostic methods can be used as an alternative, or to complement soil analyses (Ziadi et al., 2007). As corn plants age, the ratio of cytoplasm to structural tissues decreases. This normally causes a gradual decrease in shoot N and P concentrations (Hanway, 1962b; Greenwood et al., 1990; Herrmann and Taube, 2004; Ziadi et al., 2007). In addition, nutrient deficiencies cause concentrations to decrease. Jones (1983) summarized the effects of both growth stage (Hanway, 1963) and N and P deficiencies on maize shoot N and P concentrations. These data suggest that adequate whole-shoot

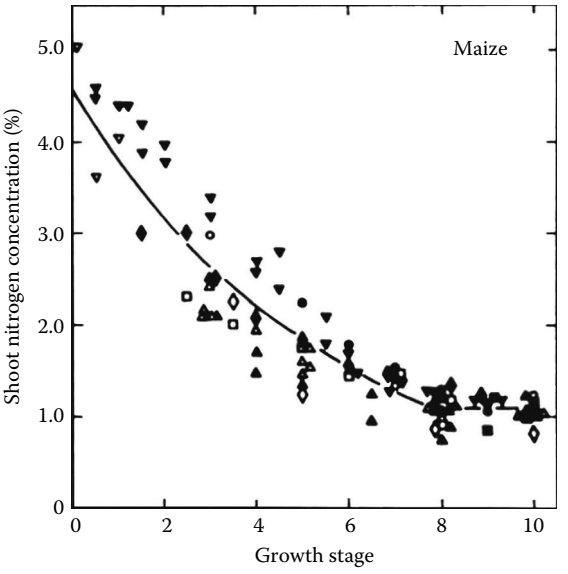

FIGURE 10.14 Relationship between growth stage and corn shoot N concentration from experiments with near-optimum N nutrition. (From Jones, C.A., *Field Crops Res.*, 6, 133, 1983.)

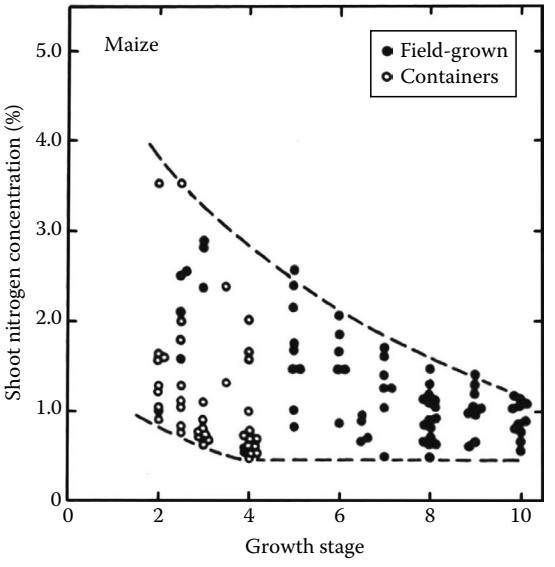

FIGURE 10.15 Relationship between growth stage and corn shoot N concentration from experiments with varying levels of N nutrition. (From Jones, C.A., *Field Crops Res.*, 6, 133, 1983. With permission.)

N concentrations decline from about 4% to 5% in the seedling stage to slightly over 1% at maturity (Figure 10.14). However, N-deficient shoots may have N concentrations as low as 0.4%–0.5% at maturity (Figure 10.15). Similarly, adequate shoot P concentrations decline from about 0.6% in the seedling to about 0.2% after silking (Figures 10.16 and 10.17).

The grain is an important sink for N. At harvest, grain N concentration ranges from about 1% to 2%, while total shoot N concentration varies from about 0.6% to 1.6% (Figure 10.18). Thus, while corn grain normally accounts for 40%–60% of shoot dry matter, it contains about 50%–80% of the nitrogen in the shoot.

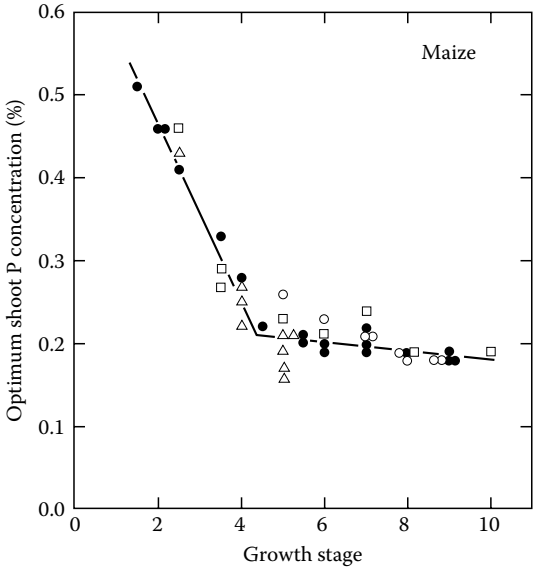

FIGURE 10.16 Relationship between growth stage and corn shoot P concentration in treatments of field experiments with near-optimum P nutrition. (From Jones, C.A., *Field Crops Res.*, 6, 133, 1983. With permission.)

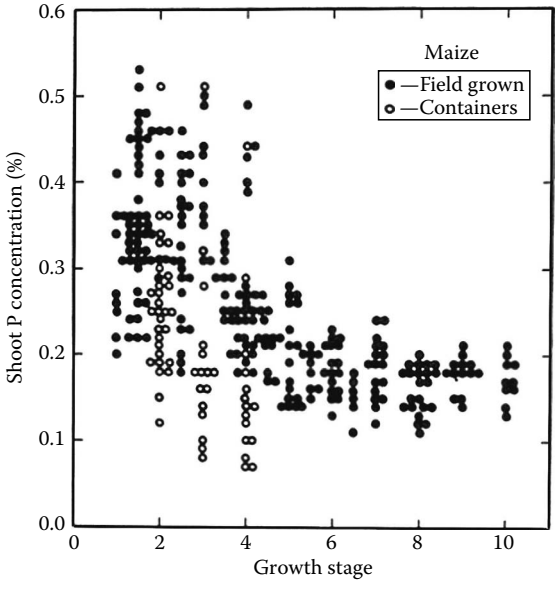

FIGURE 10.17 Relationship between growth stage and corn shoot P concentration from treatments with varying levels of P.

Relative yield increases as N concentration increases in the plant (Figure 10.19). Grain yield tends to plateau as N concentrations increase in the plant tissues. Figure 10.20 shows a good relationship is also found between soil NO_3 concentrations and relative concentrations of N in the plant. Binford et al. (1992) reported that maximum plant N concentration occurred at about 20 mg NO_3–N kg^{-1} of soil. Similarly, a relationship between K concentration in ear leaf of corn and relative grain yield is shown in Figure 10.21. The critical level of K in plant tissue at flowering was 13 g kg^{-1}.

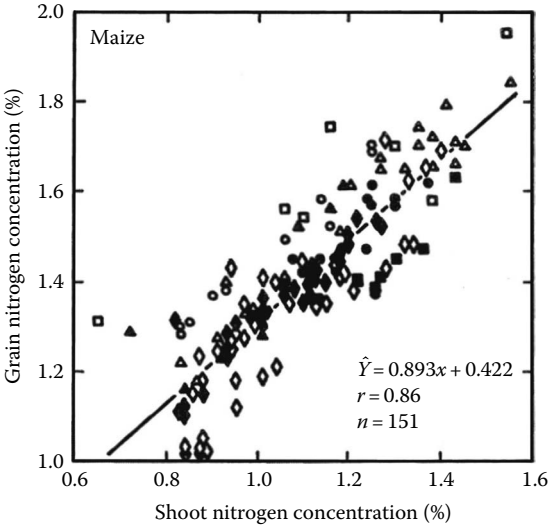

FIGURE 10.18 Relationship between corn shoot N concentration and grain N concentration. (From Jones, C.A., *Field Crops Res.*, 6, 133, 1983.)

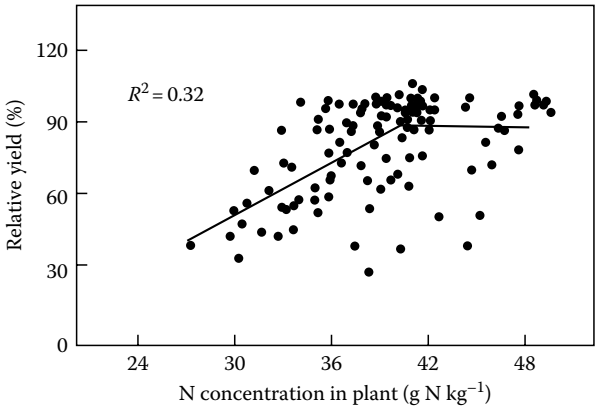

FIGURE 10.19 Relationship between relative yield and N concentration in corn plant tissue. (From Binford, G.D. et al., *Agron. J.*, 84, 219, 1992. With permission.)

Plant analysis has long been used in various ways to diagnose plant nutrient adequacy and estimate fertilizer needs. It is well known that the nutrient concentration of a plant is affected not only by the supply of that nutrient but also by supplies of other nutrients and by environmental factors. Table 10.9 provides values of adequate nutrient concentrations in corn plants at different growth stages. These values can be used as a guideline for identifying nutrient deficiencies or sufficiency levels in corn plants.

10.6 SUMMARY

Corn is the third most important cereal worldwide, after wheat and rice. It is a warm-season temperate or tropical crop grown for grain, fodder, and raw materials for industrial processes. Corn's main advantages include its high yields per unit of labor and per unit of land area. It is a compact, easily transportable source of nutrition that is relatively tolerant of pests and is easily stored. Corn is grown in a wide range of climates, from the tropics to 50° latitude and from sea level to 4000 m elevation. It tolerates a wide range of soil conditions and is grown under both irrigated and dryland conditions.

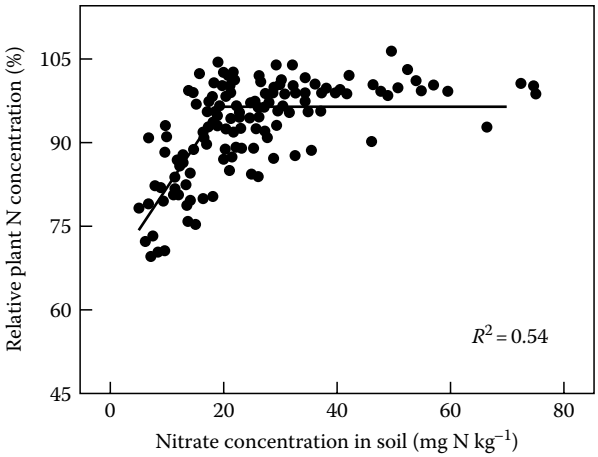

FIGURE 10.20 Relationship between nitrate concentration in soil and relative plant N concentration in the corn tissue. Relative concentrations are N concentrations in plants expressed as percentages of the mean N concentrations in plants from plots receiving the two highest rates of N fertilizer. (From Binford, G.D. et al., *Agron. J.*, 84, 219, 1992. With permission.)

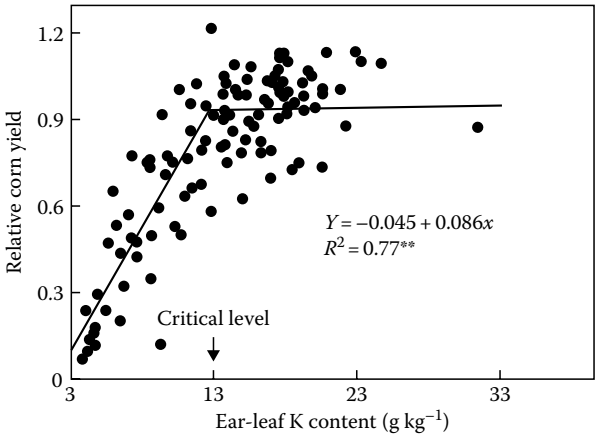

FIGURE 10.21 Relationship between K concentration of the corn leaf at flowering and relative yield. Equations apply up to the critical level. (From Cox, F.R. and Uribe, E., *Agron J.*, 84, 480, 1992. With permission.)

A crop with the C_4 photosynthetic pathway, corn has high potential growth rates. Maximum grain yields are over 12 Mg ha^{-1} in most parts of the world where corn is grown, and yields over 20 Mg ha^{-1} have been recorded under the most favorable conditions. The yields of the best farmers can approach experimental yields in developed countries, but average yields are usually much lower due to climatic, nutrient, and biological stresses. The main factors that are responsible for higher corn yields during the twentieth century are genetic improvement (hybrid era, 1939–present), and adoption of improved agronomic practices, especially increases in plant densities and the use of higher rates of nitrogen fertilizers. In addition, the release of transgenic hybrids that are resistant to insects and lodging also contributed to yield increase.

Corn is often grown in rotation with soybean, cotton, or other dicotyledonous crops to facilitate chemical weed control and because of their complementary labor and machinery requirements. In temperate climates, it is normally planted earlier and harvested later than soybeans. In many

TABLE 10.9
Adequate Levels of Nutrients in Corn Plants[a]

Nutrient	Growth Stage	Plant Part	Adequate Concentration g kg^{-1}
N	30–45 DAE	Whole tops	35.0–50.0
	Before tasseling	LB below whorl	30.0–35.0
	Silking	BOAC	>32.0
	Silking	Ear LB	28.0–35.0
P	35–45 DAE	Whole tops	4.0–8.0
	Before tasseling	LB below	2.5–4.5
	Silking	BOBC	>2.9
	Silking	Ear LB	2.5–4.0
K	30–45 DAE	Whole tops	30.0–50.0
	Before tasseling	LB below	20.0–25.0
	Silking	BOBC	>18.0
	Silking	Ear LB	17.0–30.0
Ca	30–45 DAE	Whole tops	9.0–16.0
	Before tasseling	LB below	2.5–5.0
	Silking	Ear LB	2.1–5.0
Mg	30–45 DAE	Whole tops	3.0–8.0
	Before tasseling	LB below	1.3–3.0
	Silking	Ear LB	2.1–4.0
S	30–45 DAE	Whole tops	2.0–3.0
	Silking	Ear LB	1.0–2.4
			mg kg^{-1}
Zn	30–45 DAE	Whole tops	20–50
	Before tasseling	LB below whorl	15–60
	Silking	Ear LB	20–70
Cu	30–45 DAE	Whole tops	7–20
	Before tasseling	LB below whorl	3–15
	Silking	Ear LB	6–20
Mn	30–45 DAE	Whole tops	50–160
	Before tasseling	LB below	20–300
	Silking	Ear LB	20–150
Fe	30–45 DAE	Whole tops	50–300
	Before tasseling	LB below	30–200
	Silking	Ear LB	21–250
B	30–45 DAE	Whole tops	7–25
	Before tasseling	LB below whorl	4–25
	Silking	Ear LB	6–20
Mo	<30 cm tall	Whole tops	0.1–10
	Before tasseling	LB below whorl	0.1–3
	Silking	Ear LB	>0.2

Sources: Compiled from Escano, C.R. et al., *Soil Sci. Soc. Am. J.*, 45, 1135, 1981; Jones, J.B., Jr., Interpretation of plant analysis for several crops, in *Soil Testing and Plant Analysis, Part 2*, Walsh, L.M. and Beaton, J.B. (eds.), Soil Science Society of America, Madison, WI, 40–58, 1967; Melsted, S.W. et al., *Agron. J.*, 61, 17, 1969; Neubert, P. et al., *Tabellen zur Pflanzenanelze—erste orientierrende Ubersicht,* Institut für Pflanzenernährung Jena, Berlin, Germany, 1969; Reuter, D.J., Temperature and sub-tropical crops, in *Plant Analysis: An Interpretation Manual,* Reuter, D.J. and Robinson, J.B. (eds.), Inkata Press, Melbourne, Australia, 38–99, 1986.

[a] DAE, days after emergence; LB, leaf blade; BOAC, blade opposite and above cob; and BOBC, blade opposite and below cob.

tropical areas, it is planted in association with grain legumes like common bean, and it provides physical support for climbing cultivars. It is less drought tolerant than grain sorghum and pearl millet, but it requires less water than upland rice.

Because of its high potential grain production, corn nutrient requirements can be great. Approximately 24 kg N, 3 kg P, 23 kg K, 5 kg Ca, and 4 kg Mg are removed in grain plus straw from the field to produce 1 t of grain. Both plant and soil analyses are used to diagnose and correct nutrient deficiencies and toxicities. Because of the large amounts of nutrients removed in the grain, fertilizers and manures are almost always needed to maintain soil fertility.

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11 Sorghum

11.1 INTRODUCTION

Sorghum (*Sorghum bicolor* L. Moench) is ranked fifth among cereals behind corn, rice, wheat, and barley. It is the major cereal of rainfed agriculture in the semiarid tropics (SAT). Grain sorghum is a major crop grown under semiarid conditions in the United States and other parts of the world (Bandaru et al., 2006), and it is a dietary staple of more than 500 million people in more than 30 countries (National Research Council, 1996). Over 55% of the global sorghum production is in the SAT; and of the total SAT production, Asia and Africa contribute about 65%, of which 34% is harvested in India (Sahrawat et al., 1996). Cultivated sorghum originated in northeast Africa, where the greatest diversity of types exists. The most likely area of origin is that now occupied by Ethiopia and part of Sudan, from which sorghum probably spread to West Africa (Doggett, 1970). There is evidence of sorghum in Assyria by 700 BC and in India and Europe by AD 1 (Eastin, 1983). Cultivated sorghums were first introduced to America and Australia about 100 years ago. Domestication and cultivation of sorghum has spread throughout the world, and the top 10 sorghum-producing countries and their production (in millions of metric tons) in 2007 were the United States (12.6), Nigeria (9.1), India (7.2), Mexico (6.2), Sudan (5.8), Argentina (2.8), China (2.4), Ethiopia (2.2), Burkina Faso (1.6), and Brazil (1.4) (FAO, 2009). Sorghum is the basic cereal food in parts of Asia and Africa, while in the United States and Europe it serves mainly as feed for poultry and livestock. Sorghum stems and foliage are often used as animal fodder, and in some areas, the stems are used as building material and fuel. Some sorghums have sweet, juicy stems that contain up to 10% sucrose and are chewed or used to produce syrup. Sorghum is also widely used for brewing beer, particularly in Africa, and it is among the most widely adapted of the warm-season cereals with potential for biomass and fuel production. High-energy sorghum consists of hybrids of grain and sweet sorghum types that are currently being developed for both grain and biomass production (Hons et al., 1986). They give slightly lower grain yields than conventional grain sorghums but produce large amounts of stover with high carbohydrate concentrations.

In comparing plant biomass systems for energy production, sweet sorghum is a leading contender because of its C_4 plant characteristics, with a high photosynthetic rate, large biomass yield, high percentage of easily fermentable sugars and combustible organics (fiber), tolerance to water stress, and low fertilizer requirements (Shih et al., 1981). Sweet sorghum has great potential as a field crop for sugar and ethanol production because it is adapted to a wide array of climatic and edaphic environments, whereas sugarcane can be grown only in tropical and subtropical climates. In addition, fiber from the leaves and stalks can provide the fuel required to process the extracted juice. The net energy ratio for sweet sorghum has been estimated by Sheehan et al. (1978) to exceed 1.0; that is more energy can be recovered as ethanol than is used to grow and process the crop.

11.2 CLIMATE AND SOIL REQUIREMENTS

Sorghum is adapted to tropical, subtropical, and temperate climates. Time from emergence to anthesis is affected by both photoperiod and temperature. Sorghum is a typical short day plant; four genes control its sensitivity to the photoperiod (Quinby, 1973). One of the most important achievements of grain sorghum breeders has been to reduce the photoperiod sensitivity in cultivars and thereby expand their adaptation to temperate regions with long days during the growing season (Jones, 1985).

The optimum temperature for photosynthesis is 30°C–36°C (Vong and Murata, 1977). Tiryaki and Andrews (2001a,b) reported that adequate temperatures for the germination of sorghum are 25°C–30°C (day) and 20°C–25°C (night). However, there were large differences among the genotypes. Sorghum does not tolerate frost, and most production is concentrated between latitudes 40°N and 40°S (Purseglove, 1985). Wardlaw and Bagnall (1981) found a decrease in the flow of ^{14}C-labeled photosynthates through the phloem in sorghum leaf tissue exposed to air temperatures below 10°C. Lang and Minchin (1986) reported reduced translocation in sorghum leaves after exposure to air temperatures of 3°C. These reductions in translocation were attributed to changes in membrane properties that altered the symplast/apoplast ratio of solute movement through leaf tissues. This is consistent with the response of wheat crown tissue, in which Kendal et al. (1985) found a consistent relationship between cell membrane alterations and cellular stress after freezing.

Air temperatures of −2°C or lower after anthesis reduced the test weight of grain from field-grown plants, whereas only exposure to −4°C reduced the test weight of grain from greenhouse-grown plants. As might be expected, the effects of freezing temperatures on grain test weights decrease as the plant approaches maturity. For example, exposure to −2°C for 4 h reduced caryopsis weights 81% at 200, 57% at 300, 25% at 450, and 3% at 600 growing degree days (GDD, base temperature 5.7°C) after anthesis (maturity ≈ 850 GDD) (Staggenborg and Vanderlip, 1996).

Sorghum is grown primarily in arid and semiarid regions in the world with limited or no irrigation (Xin et al., 2008). In temperate climates, it is often planted in rotation with other crops and it tolerates somewhat drier conditions than most other crops. It also tolerates temporary water logging and it can be grown on cracking clay soils with poor internal drainage. In the Southern Plains of the United States and many other areas of the world, sorghum is usually cultivated under rainfed conditions. Grain sorghum occupies the most area of any dryland row crop in Kansas (Kansas Agricultural Statistics, 1999). The yield of sorghum grown under such conditions depends on the rainfall during the growing season and the subsoil moisture stored from prior season rains (Xin et al., 2008). Sorghum is a drought resistant crop, but cultivars differ in their reactions to drought (Peng and Krieg, 1992; Mortlock and Hammer, 1999; Borrell et al., 2000). Drought resistance is related to morphological and physiological properties, including (1) slow shoot growth rate until the root system is well developed, (2) great root weight and volume and high root/shoot ratios in resistant cultivars (Nour and Weibel, 1978), (3) a larger adventitious root system and less leaf area than corn, (4) ability to reduce leaf osmotic potential and maintain turgor during stress (Ackerson et al., 1980), (5) ability to maintain relatively high leaf water potential under conditions of increasing soil moisture stress (Blum, 1974a,b), (6) ability to produce large amounts of epicuticular wax and roll leaves in time of drought to reduce water loss (Blum, 1975) and (7) stay-green or delayed foliar senescence, a trait that gives a yield advantage if rainfall after late season drought stress allows photosynthesis to resume before physiological maturity of the grain (Borrell et al., 2000).

Garrity et al. (1984) studied the stomatal behavior for different growth stages of grain sorghum and found that stomatal resistance was sensitive to small reductions in leaf water potential during the vegetative period. However, during the reproductive stage, the stomata became nearly insensitive to the leaf water potential in the plants that were irrigated weekly. Ackerson et al. (1980) observed that stomatal response to increasing water stress was altered after flowering in some sorghum hybrids. They suggested that sorghum regulates water loss by reducing ET through increases of stomatal resistance during early periods of growth and that it has the ability to adapt physiologically to water stress through osmotic adjustment during latter growth stages. Although sorghum is able to resist drought, the crop responds well to plentiful water during booting and heading, the growth stages most sensitive to drought (Salter and Goode, 1967). Hattori et al. (2008) reported that increasing the silicon concentration of hydroponic solutions increased growth, photosynthesis, and transpiration in sorghum seedlings grown under osmotic stress. Similarly, Sonobe et al. (2009) reported that silicon application improved water-use efficiency and alleviated water stress in hydroponically grown sorghum.

Craufurd et al. (1993) reported that water stress during booting and flowering stages resulted in grain yield reduction of up to 85%. Strategies such as reduced plant populations, different spacing

between rows, and skip row configurations have been used to enhance soil water contents late in the growing season (Larson and Vanderlip, 1994; Bandaru et al., 2006). Unger and Baumhardt (1999) summarized soil water storage data from 1939 through 1997 for Bushland, Texas, and found that, compared to conventional tillage, using conservation tillage during an 11 month fallow period increased average plant available soil water at planting from 100 to 170 mm. Stewart and Steiner (1990) further showed that sorghum grain yields were increased by an average of 15 kg ha^{-1} for each additional millimeter of seasonal evapotranspiration at Bushland, Texas, and so the amount of stored soil water is extremely important in this region for dryland crop production.

Sorghum can grow on a wide range of soils. It is better adapted than pearl millet to the deep cracking clays and the black cotton soils of the tropics. At the other extreme, sorghum can be productive on light, sandy soils and can be grown on soils with a wide range of pH, from 5.0 to 8.5 (Doggett, 1970).

Grain sorghum is considered to be moderately tolerant to salinity (Maliwal, 1967; Lall and Sakhare, 1970; Francois et al., 1984; Ulery and Ernst, 1997). In comparison with other cereals, grain sorghum is more sensitive to salinity than barley but less sensitive than maize (Bresler et al., 1982). Bresler et al. (1982) reported that a 10% reduction in grain yield occurs when the electrical conductivity of the saturation extract is 4.8 dS m^{-1}, and 12 dS m^{-1} causes a 50% reduction. However, Francois et al. (1984) reported that relative grain yields of two cultivars, Double TX and NK-265, were unaffected up to a soil salinity of 6.8 dS m^{-1}. Each unit increase in salinity above 6.8 m^{-1} reduced the yield by 10%. Maas et al. (1986) reported that sorghum was most sensitive to salinity during the vegetative stage and least sensitive during maturation. Similarly, Ulery and Ernst (1997) reported that over an extended length of time, the best treatment for maximizing sorghum yield utilizing saline wastewater was the application of nonsaline water early in the season to germinate and establish seedlings, followed by saline water during the grain-filling stage. Genotypic variation in sorghum salinity tolerance has been reported (Heilman, 1973; Taylor et al., 1975; Ratandilok, 1978).

11.3 GROWTH AND DEVELOPMENT

To manage the sorghum crop for maximum productivity, it is important to understand how the plant grows and develops. A brief description of the structure, growth, and development of the sorghum plant is given in this section. For more detail, readers may refer to Freeman (1970), Doggett (1970), Vanderlip (1972), Vanderlip and Reeves (1972), and Peacock and Wilson (1984).

11.3.1 Germination

Germination of the seed is the starting point for the growth and development of annual crops. It is defined as the emergence of the radicle from the seed coat. According to physiologists, germination involves uptake of water, called imbibition; mobilization of stored food reserves within the seed; and the resumption of growth and development of the embryo to form the shoot and root structures of the seedling (Fisher, 1984). Adequate moisture and suitable temperature are the two environmental requirements for germination. The germination and seedling establishment phase of sorghum is especially sensitive to cold temperatures (Tiryaki and Andrews, 2001a,b). Poor emergence and seedling death under cold temperatures results in reduced plant populations and grain yields. Tiryaki and Andrews (2001b) reported that sorghum genotypes differ significantly in germination and seedling cold tolerance. Singh (1985) found that there was a wide range of variation in cold tolerance among genotypes and concluded that several genes with cumulative effects were involved.

Seeds of tropical crops such as sorghum may not germinate satisfactorily at temperatures below 20°C but will generally germinate well at temperatures as high as 40°C. The optimum range of soil temperature for sorghum seed germination is 21°C–35°C (Kanemasu et al., 1975; Aisien and Ghosh, 1978). The lethal temperature for germination is from 40°C to 48°C (Kailasanathan et al., 1976), and there is genetic variation in germination at high temperatures (Wilson et al., 1982).

Fawusi and Agboola (1980) reported that optimum germination of sorghum seeds occurs between 25% and 50% of field capacity in a sandy loam soil. This ability to germinate at relatively low soil water contents is consistent with the results of Evans and Stickler (1961), who found near-optimum germination in mannitol solutions at osmotic potentials as low as −0.5 MPa.

Grain sorghum may exhibit seed dormancy for the first month after harvest under some conditions. Goodsell (1957) reported that seeds are often dormant soon after harvest, especially when harvested early and dried rapidly. Scarification, immersion for 1 min in water at 24°C, or immersion for 4 min at 21°C, was effective in breaking dormancy (Doggett, 1970). Genetic differences in seed dormancy have been reported (Gritton and Atkins, 1963; Parvatikar et al., 1975).

11.3.2 Roots

Roots are the plant organs responsible for water and nutrient accumulation and can influence crop yield (Merrill et al., 1996, 2002; Stone et al., 2001). They also play a major role in soil C and N cycles (Wedin and Tilman, 1990; Gale et al., 2000; Puget and Drinkwater, 2001) and may have greater influence on soil organic C and N levels than aboveground plant biomass (Boone, 1994; Norby and Cotrufo, 1998; Sanchez et al., 2002; Sainju et al., 2005). Hence, it is important to understand root structure and development. Like other grasses, grain sorghum has two distinct types of root systems. The seminal roots develop from the embryo below the scutellar node, while the adventitious roots are produced from the lower stem nodes or crown of the plant near the soil surface (Jordan et al., 1979; Zartman and Woyewodzic, 1979). Gould (1968) stated that the total number of seminal grass roots varies from one to seven. Sieglinger (1920) determined that the radicle is the only seminal (temporary) root in sorghum; however, it develops several branches. The nodal or adventitious roots develop to become the bulk of the sorghum root system. As the adventitious root system develops, there is a concomitant diminution of seminal roots as they abscise. Hackett (1973) reported the seminal root diameter of grain sorghum to be 0.2 mm and the adventitious root diameter to be 0.35 mm.

According to Kaigama et al. (1977) and Myers (1980), the maximum root weight of sorghum occurs at about anthesis, and the roots can extend to a depth of more than 1.5 m at a rate of 2–5 cm day^{-1} (Nakayama and van Bavel, 1963; Kaigama et al., 1977). Lavy and Eastin (1969) reported lateral extension of over 2 m from the crown and maximum root activity in the top 15 cm. Saint-Clair (1977) found 84% of the roots in the top 25 cm, and Mayaki et al. (1976) reported 80% in the top 30 cm. Bloodworth et al. (1958) found that, on a weight basis, 70% of the sorghum roots were in the 0–7.5 cm depth, 14% in the 7.5–15 cm depth, and 98% in the top 91 cm of the soil profile.

Significant genotypic variation has been found in sorghum root development, suggesting that sorghum could be improved by selection for more extensive root development at depth (Nour and Weibel, 1978). McClure and Harvey (1962) found that after panicle exertion hybrid grain sorghum root systems develop much more extensively and rapidly than those of the parent lines. The rate of root extension, like all characteristics of root systems, is subject to variation depending on genetic and soil factors (Russell, 1977; Stone et al., 2001). Soil factors influencing root growth rate include structure, strength, water content, temperature, porosity, gas diffusivity, pH, and fertility (Klepper, 1990; Stone et al., 2001). Improved soil management practices coupled with the selection of hybrids for deep rooting may be an effective way to increase water-use efficiency and nutrient uptake under rainfed conditions (Peacock and Wilson, 1984).

11.3.3 Stem, Leaves, and Tillers

Sorghum stems are solid, usually erect, dry or juicy, starchy or sweet, and 0.5–3 cm in diameter at the base. Plant height depends on the number of nodes and length of internodes (Purseglove, 1985). In photoperiod-sensitive cultivars, long photoperiods delay the initiation of the panicle and result in tall plants with numerous internodes.

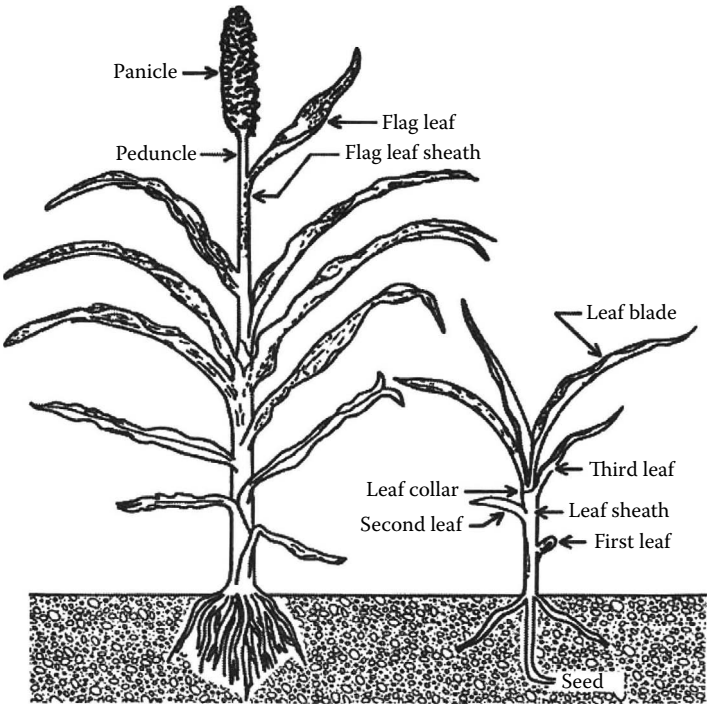

FIGURE 11.1 Mature and young sorghum plants. (From Vanderlip, R.L., *How a Sorghum Plant Develops*, Cooperative Extension Service, Kansas State University, Manhattan, KS, 1972.)

Grain sorghum exhibits a relatively simple leaf area display. As in all grasses, the leaves arise on alternate sides of the stem at the nodes and are composed of a sheath and a leaf blade, and floral initiation terminates the production of new leaves (Maas et al., 1987). Under normal field conditions, most commercial varieties of grain sorghum in the United States exhibit a unimodal distribution of leaf sizes in which individual leaf areas increase from the ground upward to a maximum value and then decrease to the top of the stalk (Maas et al., 1987). Some tall, tropically adapted varieties and plants experiencing stresses exhibit a bimodal distribution of individual leaf areas (Quinby, 1974). Figure 11.1 shows the major parts of young and mature sorghum plants.

Grass tillers are axillary shoots that grow, produce adventitious roots, and may become completely independent of the stem from which they arise. Grain sorghum cultivars vary in their tendency to produce tillers (Escalada and Plucknett, 1975; Isbell and Morgan, 1982), and environmental conditions can stimulate or retard their production. For example, defoliation or death of the main stem reduces apical dominance and permits rapid tiller production.

11.3.4 Inflorescence

The inflorescence is a compact to open panicle with primary branches arising from a central rachis. These give rise to secondary and sometimes tertiary branches that carry the racemes of spikelets (Doggett, 1970). The racemes bear spikelets in pairs; one of each pair is sessile and fertile, and the other is pedicled and male or sterile. The sessile spikelet has two glumes that enclose two florets. The upper floret is perfect; the lower is sterile and consists of a lemma that partially enfolds the fertile floret (Doggett, 1970). Anthesis begins near the tip of the panicle 0–3 days after the emergence from the boot. Flowering proceeds basipetally for 4–7 days. Sorghum is generally a self-pollinated plant, but some cross-pollination always occurs.

TABLE 11.1
Growth Stages of Sorghum

Growth Stage	Approximate Days after Emergence	Identification Characteristic
0	0	Emergence. Coleoptile visible at soil surface.
1	10	Collar of third leaf visible.
2	20	Collar of fifth leaf visible.
3	30	Growing point differentiation. Approximately 8-leaf stage by previous criteria.
4	40	Final leaf visible in whorl.
5	50	Boot. Panicle extended into flag leaf sheath.
6	60	Half-bloom. Half of plants at some stage of bloom.
7	70	Soft dough.
8	85	Hard dough.
9	95	Physiological maturity. Maximum dry matter accumulation.

Source: Vanderlip, R.L., *How a Sorghum Plant Develops*, Cooperative Extension Service, Kansas State University, Manhattan, KS, 1972. With permission.

The onset of the reproductive phase commences with the initiation of the panicle, which usually occurs between 30 and 40 days after emergence but may vary according to genotype and environmental conditions (Peacock and Wilson, 1984). The grain attains maximum dry weight 25–55 days after blooming. The air-dried whole grain contains 8%–16% water, 8%–15% protein, 2%–5% fat, 68%–74% carbohydrates, 1%–3% fiber, and 1.5%–2.0% ash (Purseglove, 1985).

11.3.5 Growth Stages

Correct identification of growth stages is very important for tissue sampling for nutrient analysis; top dressing of nitrogen; control of pests, diseases, and insects; irrigation; and harvesting. Table 11.1 describes the different growth stages of sorghum plants. Although cultivar, temperature, and (sometimes) photoperiod affect the duration of growth stages, the same general pattern is found in early, medium, and late maturity hybrids (Vanderlip and Reeves, 1972).

11.3.6 Dry Matter Production

Sorghum is a C_4 crop with a high CO_2 assimilation capacity and potentially high rates of dry matter production. Leaf photosynthetic rates of over 72 mg CO_2 dm^{-1} ha^{-1} have been reported under field conditions (Rawson et al., 1978; Eastin, 1983). Typical patterns of dry weight development and partitioning among different plant parts are shown in Figure 11.2. In the first 30–35 days of plant growth, shoot dry matter consists primarily of leaves. The culm or stalk then begins rapid growth, and both leaf and stalk weights increase until they reach their maximum values at about 60–65 days, respectively. Panicle weight increases rapidly from 50 to 60 days, and after pollination the grain weight increases rapidly.

Eck and Musick (1979) found that the dry matter accumulation rate of grain sorghum was nearly constant from about 40 days after planting until near physiological maturity (115 days). About 59% of the total dry matter had accumulated by flowering. Leaf blades reached their maximum weight 7 days after the boot stage and maintained that weight until near maturity. Stalk weights reached their maximum 7 days after half bloom and declined from then on until maturity. At maturity, stems, leaves, and panicles contained 18%, 24%, and 58% of the total dry matter, respectively. Roy and Wright (1973) reported that the contributions of stems, leaves, and panicles to the total dry

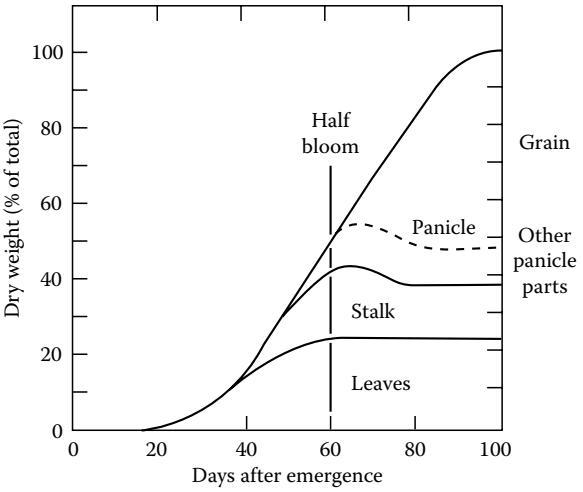

FIGURE 11.2 Dry weight of different plant parts of grain sorghum as a function of plant age. (From Vanderlip, R.L., *How a Sorghum Plant Develops*, Cooperative Extension Service, Kansas State University, Manhattan, KS, 1972.)

matter yield were 32%, 18%, and 50%, respectively, for a well fertilized ($N_{120}P_{26}$ kg ha^{-1}) treatment, but they were 41%, 23%, and 36% for an unfertilized treatment.

11.3.7 Leaf Area Index

Leaf area index (LAI) is often used as an indicator of plant growth and for evaluating assimilation and transpiration rates in plant physiological studies. It is also frequently used in agronomic studies to model yield and to make crop production decisions (Hodges and Kanemasu, 1977). Grain yield of annual crops is usually related to the duration of leaf area, and the establishment of a high leaf area index as early as possible is important in order to obtain maximum yield. Large plant populations, narrow row spacing, and large seeds can contribute to early leaf area development (Doggett, 1970).

In cereals most of the carbohydrate in the grain results from photosynthesis after heading, though reallocation of assimilates from the stem often accounts for 10%–12% of the total grain weight (Fischer and Wilson, 1971; Chamberlin and Wilson, 1982). Because of the importance of post-anthesis photosynthesis, the longer leaf area is retained after heading, the more assimilates are available for grain growth. This leaf area duration may be affected by mineral nutrition; especially N. Nitrogen deficiency and retranslocation of N from the leaves to the grain seed leaf cause senescence and reduce the duration of the leaf area after heading (Yoshida, 1972). Maximum leaf area index in sorghum is usually achieved just before anthesis, and an LAI of approximately 5, is found in productive commercial fields in the United States. Fields in drier areas can have LAI values of 2–4 (Eastin, 1983).

Both "senescent" and "nonsenescent" genotypes of sorghum are known. Leaves of the senescent genotypes senesce soon after the physiological maturity of the grain. In contrast, leaves of nonsenescent genotypes remain green and contribute to the accumulation of starch and sucrose in the culms (McBee et al., 1983).

11.4 YIELD AND YIELD COMPONENTS

The highest grain yields reported for sorghum are 16.5 (Pickett and Fredericks, 1959) and 14.25 Mg ha^{-1} (Fischer and Wilson, 1975). The harvest index for the latter was 0.45, and the total aboveground dry matter was 31.7 Mg ha^{-1}. Average worldwide yields are about 1.3 Mg ha^{-1}, ranging from as low as 0.66 t ha^{-1} in parts of Africa to as high as 4 Mg ha^{-1} in Latin America (Peacock and Wilson, 1984).

Sorghum grain yield can be expressed by the equation (Quinby, 1973):

$$\text{Yield} = \text{No. of plants (P)} \times \text{panicles or heads per plant (H)} \times \text{seeds per head (S)} \times \text{weight per seed (W)}$$

High yield can be obtained only if all yield components are at optimum levels. This requires adequate plant population, adequate water and nutrients, optimum crop management, and a cultivar with high yield potential. Hybrid vigor (heterosis) is great in commercial grain sorghum hybrids. A greater number of seeds per plant has been recognized as the yield component that contributes the most to heterosis (Quinby, 1973). The grain harvest index (GHI) is an important plant trait in improving sorghum yield. Winter and Unger (2001) reported that the GHI of sorghum varied from 0.38 to 0.49 depending on tillage treatments. These authors also reported that in ungrazed-wheat-fallow-sorghum production systems the conservation tillage improved sorghum grain yield by 10%–20% compared with conventional tillage because of greater soil water storage during the fallow with conservation tillage.

11.5 NUTRIENT REQUIREMENTS

Nutrient requirements vary according to soil, climate, and cultivar. The purpose of this discussion is to develop a conceptual framework concerning nutrient requirements of the crop. The best way to determine specific rates of nutrients for a given crop is to determine the yield potential, the amounts of nutrients required to produce the potential yield, and the amount of mineral nutrients that can be furnished by the soil. Soil tests, yield response curves, and visual assessment of deficiency and/or toxicity symptoms are the important methods for diagnosing nutritional disorders. These techniques have been discussed in detail in Chapter 4.

Development of better adapted, higher yielding sorghum cultivars has increased both the yield potential and the amounts of plant nutrients required by the crop (Wortmann et al., 2007). Consequently, fertilizer application to sorghum has increased tremendously. Nitrogen, phosphorus, and potassium are the essential elements required in relatively large quantities. Nutrient inputs are one of the important components of improved farming systems within the assured rainfall area (>800 mm annual rainfall) of the Indian SAT. Deficiencies of N and P are common for crops such as sorghum (Katyal and Das, 1993). Limon-Ortega et al. (1998) reported that N application of 78 kg ha^{-1} increased sorghum grain yields by an average of 1.15 Mg ha^{-1} compared to control treatment under normal rainfall conditions. Similarly, reducing row spacing from 76 to 38 cm increased grain yields by an average of 1.06 Mg ha^{-1} with adequate seasonal precipitation. Villar et al. (1989) also reported that sorghum grain yields increased with N fertilizer application and as the row spacing was narrowed from 76 to 36 cm, unless rainfall was severely limiting.

Under rainfed cropping in India, it is generally understood that if soil test P (0.5 M $NaHCO_3$, Olsen P) is less than 5 mg kg^{-1} soil, a response to applied P is likely (El-Swaify et al., 1985). Recent research at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) confirmed this rule for alfisols in which substantial responses to fertilizer P were obtained when the Olsen P was greater than 2.5 but less than 5 mg kg^{-1}. However, sorghum grown on Vertisols responded little to applied P unless the extractable P by Olsen was less than 2.5 mg kg^{-1} soil (Sahrawat, 1988). In the Vertisol, 90% relative grain yield of sorghum was obtained at 2.8 mg kg^{-1} Olsen extractable P while in the Alfisol, 90% relative grain yield was achieved at 5.0 mg P kg^{-1} soil. These results suggest that the critical value for available P is lower for the clayey Vertisol than the sandy Alfisol (Sahrawat, 1988; Sahrawat et al., 1996).

In the United States, most grain sorghum is grown on soils that are well supplied with calcium and magnesium (Tucker and Bennett, 1968). However, at soil pH values less than 5.5, the aluminum toxicity and Ca and Mg deficiencies can reduce yields. Abruna et al. (1982) reported that in Puerto Rico grain sorghum yields were reduced when aluminum saturation exceeded 10%, and no yield

was obtained when toxicity exceeded 80%. Other cases of Al toxicity have been reported in soils of the semiarid and subhumid zones of West Africa (Doumbia et al., 1993). Dolomitic lime is often applied to acid soils to reduce aluminum toxicity and to supply adequate calcium and magnesium. However, the use of acid-tolerant genotypes can be a complementary solution, and conventional breeding systems have been used for the improvement of acid soil tolerance (Duncan, 1987; Gourley et al., 1990). Recently, biotechnology has been utilized to produce somaclonal variation in sorghum, and somaclonal variation for agronomic, physiological, and morphological traits has been reported (Miller et al., 1992). Lines of sorghum regenerated from tissue culture demonstrated improved acid soil tolerance under field conditions, and improved root development at low pH (4.2–4.6) during the seedling stage (Miller et al., 1992). Baligar et al. (1993a,b) studied growth and nutrient uptake behavior of Al-sensitive and Al-tolerant sorghum genotypes under field conditions. Aluminum-tolerant entries had higher shoot and root weight, shoot: root ratio, tolerance index, and nutrient concentrations than Al-sensitive entries (Table 11.2).

Genetic diversity for N use efficiency (NUE) has been demonstrated in sorghum, with some of the most efficient types being cultivars developed in low fertility environments (Gardner et al., 1994; Maranville and Madhavan, 2002; Crawford et al., 2009). Therefore, exploiting genotypic differences in N demand and efficiency have been proposed as possible alternatives for reducing reliance on fertilizer N. However, little is known about the combination of morphological, anatomical, and physiological factors that contribute to improved NUE. Landraces that have evolved in low N environments may possess different mechanisms for coping with stress than cultivars developed in contemporary breeding programs (Pearson, 1985). Physiological processes related to N stress tolerance can produce genotypic variation in leaf area, gas exchange rates, and stomatal conductance per unit of leaf N (Pavlik, 1983). Leaf morphological and anatomical features can also influence these physiological processes and contribute to NUE (Longstreth and Nobel, 1980; Pavlik, 1983). Leaf size (Bhagsari and Brown, 1986), leaf thickness (Alagarswamy et al., 1988) and internal leaf anatomy (Nobel et al., 1975) have all been associated with photosynthetic N efficiency.

TABLE 11.2
Average Response of Growth Traits and Nutrient Concentrations for Al-Sensitive and Al-Tolerant Sorghum Genotypes

Plant Parameter	Al-Sensitive	Al-Tolerant
Shoot dry weight g plant^{-1}	0.09	0.34
Root dry weight g plant^{-1}	0.06	0.14
Shoot: root ratio	1.52	2.49
Al tolerance index for shoot (%)[a]	22.00	61.00
Al tolerance index for root (%)[a]	26.00	58.00
N concentration (mg g^{-1})	29.1	33.1
P concentration (mg g^{-1})	1.3	1.6
K concentration (mg g^{-1})	16.5	28.7
Ca concentration (mg g^{-1})	3.1	4.0
Mg concentration (mg g^{-1})	1.4	1.7
Zn concentration (mg g^{-1})	65.6	138.7
Fe concentration (mg g^{-1})	209.6	263.3

Source: Baligar, V.C. et al., *Agron. J.*, 85, 1068 1993a; Baligar, V.C., *Plant Soil*, 150, 271, 1993b. With permission.

[a] Al tolerance index = (Growth with Al/Growth without Al) × 100.

In areas where soil pH and calcium content are high, the availability of certain micronutrients, including iron, zinc, manganese, and copper, may be restricted. Of these, iron deficiency is the most common; therefore, more studies have been conducted on iron chlorosis in sorghum than on other micronutrients (Tucker and Bennett, 1968). Iron deficiency on calcareous soils causes dramatic but usually localized decreases in grain sorghum growth. These areas of iron deficient plants are visible from a distance because of dramatic decreases in growth and severe chlorosis. Symptoms are usually most severe on the most recently expanded leaves, but all leaves may be affected in severe cases. Iron applied in foliar sprays is rapidly incorporated into proteins, but its translocation to younger leaves is usually inadequate to prevent their chlorosis. Thus, multiple foliar applications are often needed. For example, Withee and Carlson (1959) reported that three applications were needed for maximum grain sorghum yields.

In general, grain sorghum and corn are somewhat more susceptible to iron deficiency than most dicots (Brown, 1978). However, significant genotypic differences in sensitivity to iron deficiency have been observed in grain sorghum (Brown and Jones, 1975; Williams et al., 1982). This is probably due to the inability of sensitive genotypes to excrete H^+ and organic reducing agents from the roots.

Most of the tropical soils where sorghum is grown are subject to deterioration with agricultural use, mainly because of a decrease in organic matter content. Management practices that control the amounts of organic matter are therefore an important aspect of soil management for sorghum production.

11.5.1 Nutrient Uptake

One general guideline for nutrient needs is the nutrient removal by the crop. Figures 11.3 through 11.5 show N, P, and K uptake and distribution among various sorghum plant parts during growth. Large quantities of N and P and some potassium are translocated from the other plant parts to the grain as it develops. Unless adequate nutrients are available during grain filling, this translocation may cause deficiencies in the leaves and premature leaf loss that reduce leaf area duration and may decrease yields. Thus, an adequate supply of nutrients at all stages of development of the plant is necessary for maximum yields (Vanderlip, 1972).

Figures 11.3 through 11.5 show that a large portion of the N and P but only a small portion of potassium is removed in the grain. Amounts removed depend on nutrient concentrations and total

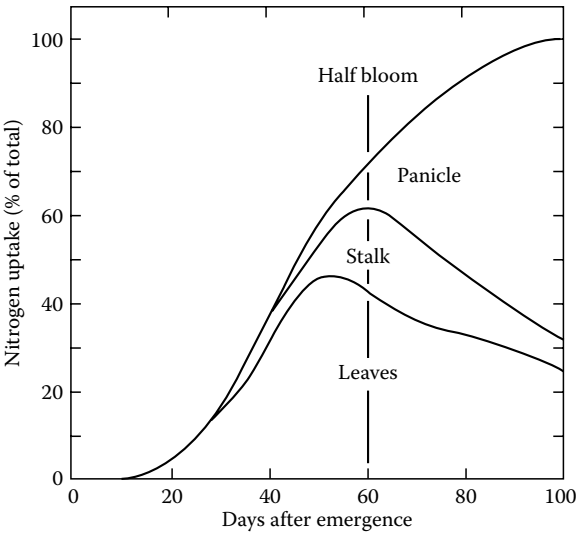

FIGURE 11.3 Nitrogen uptake in different parts of sorghum plant during crop growth. (From Vanderlip, R.L., *How a Sorghum Plant Develops*, Cooperative Extension Service, Kansas State University, Manhattan, KS, 1972.)

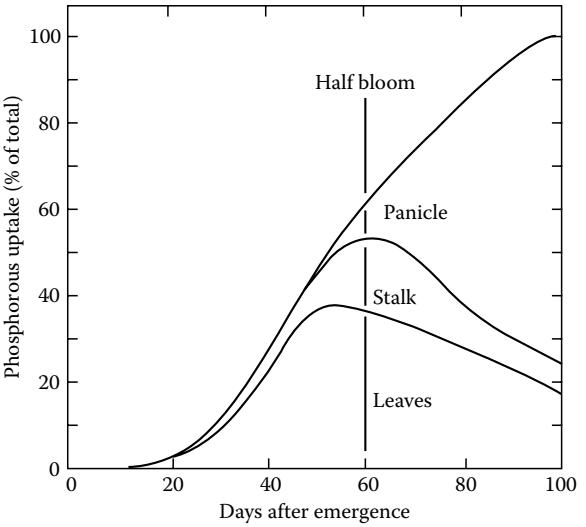

FIGURE 11.4 Phosphorus uptake in different parts of sorghum plant during crop growth. (From Vanderlip, R.L., *How a Sorghum Plant Develops*, Cooperative Extension Service, Kansas State University, Manhattan, KS, 1972.)

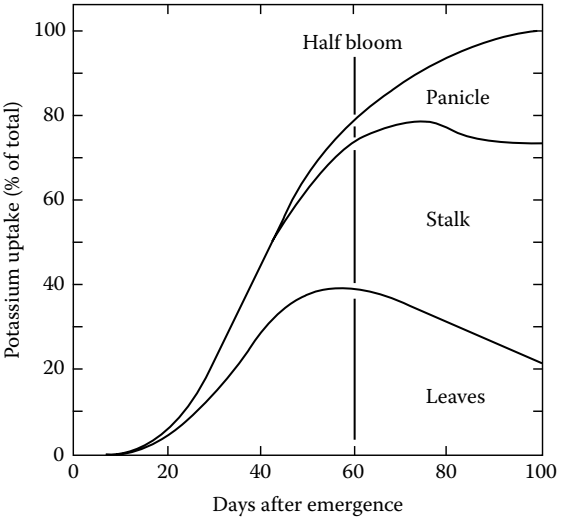

FIGURE 11.5 Potassium uptake in different parts of sorghum plant during crop growth. (From Vanderlip, R.L., *How a Sorghum Plant Develops*, Cooperative Extension Service, Kansas State University, Manhattan, KS, 1972.)

grain production. According to Vanderlip (1972), a grain crop of 8500 kg ha^{-1} contains (in the total aboveground plant) 207 kg of N, 39 kg of P, and 241 kg of K. If the entire plant is harvested for silage or other forms of feed, much more potassium is removed because most of it is in the vegetative part of the plant. Jones (1983) reported that in a number of experiments the mean N concentration in the grain was 1.67% with a range of 1.02%–3.20%. Mean N concentration of the stover was 0.80% with a range of 0.36%–1.26%.

Pal et al. (1982) reviewed the 25 years of research in India on the mineral nutrition and fertilizer response of grain sorghum. Accumulations of N, P, and K by grain sorghum were characterized. Usually N and P accumulated slowly compared with the rapid accumulation of K in the early stage of crop growth. In later stages, uptake of K decreased relative to that of N and P. Most of

the K remained in the stalk and leaves, while most N and P accumulated in the panicle. Fertilizer responses to N and P were observed throughout India. Improved varieties and hybrids of sorghum responded to N rates ranging from 60 to 150 kg N ha^{-1}, whereas a response to P application was observed up to 40 kg P ha^{-1}. Response to K was inconsistent, depending on the K-supplying power of soils. A balanced fertilizer schedule consisting of 120 kg N ha^{-1}, 20 kg P ha^{-1}, 33 kg K ha^{-1}, and 15–25 kg $ZnSO_4$ ha^{-1} was recommended for improved productivity of grain sorghum. Sahrawat et al. (2008) reported that balanced nutrition of rainfed sorghum not only increases yields but also enhances N, S, and Zn contents in the grain and straw.

Diagnosis of nutrient deficiencies requires a knowledge of tissue nutrient concentrations that are needed for maximum growth rates. Lockman (1972a,b,c) provided estimates of adequate nutrient concentration ranges of several nutrients for grain sorghum tissues at different growth stages. These ranges were summarized from a large body of data and were thus wide. Jones (1983) subsequently attempted to define the variability in N and P concentrations in sorghum. He attempted to normalize the concentrations by expressing them as functions of the numerical growth stage system described by Vanderlip and Reeves (1972). Lockman (1972c) correlated plant nutrient concentrations and grain yields at various growth stages of sorghum, as shown in Table 11.3. Nitrogen and phosphorous concentrations were well correlated with yields at all growth stages. Potassium concentrations were correlated with grain yield only for seedling and vegetative samples. Calcium concentrations were only moderately correlated with yield, generally in a negative manner. Magnesium concentrations in grain-sorghum plant samples were poorly correlated with yield. Boron, copper, iron, manganese, and aluminum concentrations were not well correlated with yields. Zinc levels in grain-sorghum plant samples showed curvilinear correlations with grain yield.

Deficient, low, adequate, and high values for grain sorghum nutrient concentrations at different growth stages are presented in Table 11.4. These values can be used as guidelines in the nutritional diagnosis of the crop. Many breeding programs with forage sorghum have emphasized agronomic performance (adaptation, pest resistance, and forage yield and quality), paying little attention to the genotypic differences in mineral concentrations (Kidambi et al., 1993). Mineral concentrations may vary due to genotype, stage of plant development, plant part sampled, time of sampling, and soil

TABLE 11.3
Correlation between Plant Nutrient Concentrations and Grain Yield at Various Growth Stages[a]

Element	Seedling (Stage 2)	Early Vegetative (Stage 3)	Late Vegetative (Stage 4–5)	Bloom (Stage 6)	Fruiting (Stage 7–8)
N	++	++	++	++	+V
P	++	++	++	++	+V
K	++	++	++	–	0
Ca	+	=	=	–	–
Mg	–	–	–	=	–0
B	0+	0	0	0	–0
Cu	0	0	0	0–	0
Fe	–	0–	0–	0	0
Mn	V	V	V	V	–
Zn	V	V	V	0–	0
Al	0–	0–	0	0	0–

Source: Lockman, R.B., *Commun. Soil Sci. Plant Anal.*, 3, 295, 1972c. With permission.

[a] Degree and direction indicated: ++, good, positive correlation; +, fair, positive correlation; 0, no correlation; –, fair, negative correlation; =, good, negative correlation; V, correlation variable or dependent on other conditions.

TABLE 11.4
Nutrient Concentrations in Sorghum Plants

Nutrient	Growth Stage	Plant Part[a]	Deficient	Low	Adequate	High
			g kg^{-1}			
N	Seedling	Whole tops	<35	30–40	35–51	>51
	Early vegetative	Whole tops	10	30	30–40	>40
	Vegetative	YMB	—	<32	32–42	>42
	Bloom	3BBP	<25	25–23	33–40	>40
P	Seedling	Whole tops	<2.5	2.5–3.0	3.0–6.0	<6.0
	Early vegetative	Whole tops	1.0	1.0–2.0	2.1–5.0	<5.0
	Vegetative	YMB	<1.3	1.3–2.5	2.0–6.0	—
	Bloom	3BBP	<1.3	1.3–1.5	1.5–2.5	<2.5
K	Seedling	Whole tops	<25	25–30	30–45	>45
	Early vegetative	Whole tops	15	16–25	25–40	>40
	Vegetative	YMB	<15	15–20	20–30	>30
	Bloom	3BBP	—	—	10–15	—
Ca	Seedling	Whole tops	—	<12	9–13	>13
	Early vegetative	Whole tops	2.4	3.0–10.0	10–15	>15
	Vegetative	YMB	—	—	1.5–9.0	>9
	Bloom	3BBP	—	<2.0	2.0—6.0	>6
Mg	Seedling	Whole tops	—	3.0–3.4	3.5–5.0	>5
	Early vegetative	Whole tops	2.0	2.0–3.0	4.0–8.0	>8
	Vegetative	YMB	—	—	2.0–5.0	>5
	Bloom	3BBP	—	1.0–2.0	2.0–5.0	>5
S	Vegetative	Whole tops	<0.3	2.0–2.5	2.5–3	>3
			mg kg^{-1}			
Fe	Seedling	Whole tops	—	—	160–250	>300
	Early vegetative	Whole tops	<30	—	90–120	—
	Vegetative	YMB	—	—	55–200	>200
	Bloom	3BBP	—	—	65–100	—
Mn	Seedling	Whole tops	—	—	40–150	>150
	Early vegetative	Whole tops	<15	11–14	40–70	>70
	Vegetative	YMB	—	<10	6–100	>100
	Bloom	3BBP	—	<10	8–190	>190
Zn	Seedling	Whole tops	—	<30	30–60	>60
	Early vegetative	Whole tops	<16	16–20	20–50	>50
	Vegetative	YMB	—	<20	20–40	—
	Bloom	3BBP	—	<15	15–30	—
Cu	Seedling	Whole tops	—	—	8–15	>15
	Early vegetative	Whole tops	—	<3	3–14	—
	Vegetative	YMB	—	—	2–15	>15
	Bloom	3BBP	—	—	2–7	>10
B	Seedling	Whole tops	—	<4	4–13	—
	Early vegetative	Whole tops	<3	3–10	10–15	>25

(*continued*)

TABLE 11.4 (continued)
Nutrient Concentrations in Sorghum Plants

Nutrient	Growth Stage	Plant Part[a]	Deficient	Low	Adequate	High
			mg kg^{-1}			
	Vegetative	YMB	—	—	1–10	—
	Bloom	3BBP	—	—	1–10	—

Sources: Compiled from Jones, J.B., Jr. and Eck, H.V., Plant analysis as an aid in fertilizing corn and grain sorghum, in *Soil Testing and Plant Analysis*, Walsh, L.M. and Beaton, J.D. (eds.), Soil Science Society of America, Madison, WI, 349–364, 1973; Lockman, R.B., *Commun. Soil Sci. Plant Anal*., 3, 295, 1972c; Reuter, D.J., Temperate and subtropical crops, in *Plant Analysis: An Interpretation Manual*, Reuter, D.J. and Robinson, J.B. (eds.), Inkata Press, Melbourne, Australia, 38–99, 1986. With permission.

[a] YMB, youngest (uppermost) mature leaf blade; 3BBP, third blade below panicle.

fertility. Mineral imbalances or shortfalls may be corrected in the short term by mineral supplementation and in the long term through plant breeding and genotype selection.

11.6 SUMMARY

Sorghum is a warm temperate and tropical cereal with the C_4 photosynthetic pathway and is one of the five major crops of the world. It originated in northeastern Africa in prehistory and is used as a source of food, feed, and industrial raw material. Sorghum has been cultivated for food since ancient times in arid and semiarid regions of Africa and India, where productivity and the area cultivated have remained relatively stable in the recent past. Traditional sorghum cultivars used in these countries are tall, sensitive to photoperiod, and have a low harvest index due to excessive production of stem tissue. In contrast, productivity and the area cultivated have increased spectacularly in countries like the United States, Mexico, and Argentina, where hybrid vigor has been exploited through the use of cytoplasmic male sterility. Other factors responsible for yield increases include the development of short cultivars with increased harvest index (0.4–0.5), decreased photoperiod sensitivity, and increased disease and insect resistance, as well as improved management. Potential sorghum grain yields are over 14 Mg ha^{-1}, but average farmers' yields worldwide are only about 1.3 Mg ha^{-1}.

Sorghum can be grown on a wide range of soils with pH values ranging from 5 to 8.5. It is normally more tolerant of drought stress than corn, and it is often grown in areas that are too dry for consistent corn production. Nitrogen is usually the most limiting plant nutrient, and 1 metric ton of sorghum grain contains about 18 kg N, 3 kg P, and 4 kg K. Both soil and plant analysis can be used for the diagnosis and correction of nutrient deficiencies and toxicities.

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12 Soybean

12.1 INTRODUCTION

The soybean is the most important grain legume crop in the world in terms of its use in human foods and livestock feeds. Soybean is unique in having high concentrations of both oil and protein. It has the highest protein concentration of all edible legumes (Breene et al., 1988; Kumudini et al., 2005). Approximately one-third of the world's edible oils and two-thirds of the world's protein meal are derived from soybean (Golbitz, 2004; Temperly and Borges, 2006). The soybean belongs to the family Leguminosae, subfamily Papilionoideae, and the genus *Glycine* L. The cultivated species is *Glycine max* (L.) Merrill. Soybean apparently originated in China and was introduced into Europe in the early 1700s and into North America in the early 1800s (Whigham, 1983). Important soybean-producing countries are the United States, Brazil, China, and Argentina. The eight major soybean-producing countries in 2007 were the United States (72.9 million metric tons, Mt), Brazil (57.9 Mt), Argentina (47.5 Mt), China (13.8 Mt), India (11.0 Mt), Paraguay (5.86 Mt), Canada (2.70 Mt), and Bolivia (1.60 Mt). Since 1970, soybean production has been at least double that of any other oilseed crop. The improvement in soybean production is associated with both improvements in genetics as well as management practices. Two management practices that have revolutionized soybean production in most of the soybean-producing countries are reduced row spacing or increasing plant populations and release of glyphosate (herbicide)-resistant cultivars. Bertram and Pedersen (2004) reported that, averaged across weed management systems and plant populations, 19 and 38 cm rows yielded 7%, 9%, and 10% more than 76 cm rows in southern, central, and northern Wisconsin, respectively. Soybean planted in narrow rows (<76 cm) intercept more sunlight than wide rows (Bertram and Pedersen, 2004) and suffer less weed competition (Forcella et al., 1992). Similarly, glyphosate-resistant soybean was one of the first major successes of genetic engineering (Padgette et al., 1996). King et al. (2001) reported advances in biotechnology resulting in glyphosate-tolerant soybean cultivars, providing an effective broad-spectrum postemergence weed control option. Glyphosate applied at labeled rates does not affect glyphosate-resistant soybean adversely (Nelson and Renner, 1999).

Soybean yields have steadily increased in the past 30 years due to a combination of improved genetics and management (Salvagiotti et al., 2008). The annual rate of yield increase has averaged 31 kg ha^{-1} in the United States (Specht et al., 1999; Kumudini, 2002) and 28 kg ha^{-1} globally (Wilcox, 2004). Although soybean use for biodiesel production may require expansion of land area devoted to soybean in some parts of the world, such an expansion is not likely in North America because of increased competition for land by the rapidly rising corn ethanol industry (Salvagiotti et al., 2008). In the U.S. Corn Belt region, soybean yield potential has been estimated to be in the range of 6–8 Mg ha^{-1} (Cooper, 2003). In order to achieve high yield potential, soybean must sustain high photosynthesis rates and accumulate large amounts of N in the seed. Nitrogen exists in leaves primarily as ribulose biphosphate carboxylase/oxygenase and there is generally a strong relationship between N per unit leaf area and photosynthesis (Sinclair, 2004). Hence, yield increases will become the major source for sustaining further increases in soybean production, particularly in North America. The design of soil and crop management strategies that fully exploit the climatic and genetic potential of soybean remains a key challenge to achieve this goal (Salvagiotti et al., 2008).

The contribution of soybean to world oilseed production increased from 32% in 1965 to over 50% in the 1980s (Smith and Huyser, 1987). Several important factors contributed to the rapid increase in soybean production, including a steady expansion in the market for soybean oil and meal

in various parts of the world. Soybean seeds contain approximately 21% oil and 41% protein on a dry weight basis (Johnson and Bernard, 1962; Hartwig and Kilen, 1991; Wilson, 2004; Ray et al., 2006; Naeve et al., 2008) and provide a valuable food for human consumption. Soybean meal is becoming increasingly important in the production of high protein foods and drinks for human consumption (Robson et al., 2002). Soybean oil is used for human food; in various pharmaceuticals and medicines; and in manufacturing disinfectants, printing inks, and soaps. Various soybean food products are used for human consumption, including fermented food; soy beverage; flour; whole-bean confectionery products; and textural vegetable protein used as simulated meat, fruit, and nut products (Chomchalow et al., 1993; Whigham, 1983; USB, 2000). After processing, the by-products of the seeds of soybean provide a valuable, protein-rich feed supplement for livestock. Soybean provides about 52% of the world's conventional oilseeds (Robson et al., 2002) and was the fourth largest grain crop in terms of production in 2007, with 221 Mt, compared with 792 Mt of corn, 660 Mt of rice, and 606 Mt of wheat (FAO, 2009).

12.2 CLIMATE AND SOIL REQUIREMENTS

Soybean is a warm-season crop, but cultivation now extends from the tropics to 52°N. The major commercial production of soybean is between 25° and 45° latitude and at altitudes of less than 1000 m. The general climatic requirements are approximately those of corn, and the greatest development in the United States has been in the corn belt (Purseglove, 1987). Soybean is a photoperiod-sensitive short-day plant that has been successfully adapted to 13 maturity groups corresponding to narrow zones of latitude. Cultivars are assigned to maturity groups according to their photoperiod requirements for maturity (Fehr, 1987). Five major genes that affect the time of flowering and maturity have been identified (Wilcox et al., 1995). Although expression of these genes is influenced by interactions with latitude, temperature, and photoperiod, environmental effects are thought to be small compared with genotypic effects (McBlain et al., 1987; Wilcox et al., 1995).

Soybean is temperature sensitive and usually grown in environments with temperatures between 10°C and 40°C during the growing season (Whigham, 1983). Controlled environment studies using season-long temperature treatments have shown that final soybean seed yield increased as temperature increased between 18/12 (day/night) and 26°C/20°C, but yield decreased when plants were grown at temperatures greater than 26°C/20°C (Sionit et al., 1987). Night temperature increases from 10°C to 24°C increased soybean seed yield (Seddigh and Jolliff, 1984a,b). Raising temperatures from 29°C/20°C to 34°C/20°C during seed fill decreased soybean seed yield (Dornbos and Mullen, 1991). Day/night temperatures of 30°C/20°C, 30°C/30°C, 35°C/20°C, and 35°C/30°C were imposed during flowering and pod set (R_1–R_5), seed fill and maturation (R_5–R_8), and during the entire reproductive period (R_1–R_8) (Gibson and Mullen, 1996). Increases in day temperature resulted in decreased seed formation when plants were exposed during flowering and pod set and decreased growth when exposed during flowering and pot set or seed fill. Seed growth reductions in plants exposed to the high day temperature were accompanied by decreased photosynthetic rates. The largest yield reduction in this study was 27% and occurred when 35°C occurred for 10 h per day from flowering to maturity. No significant losses in yield occurred at high night temperature at any reproductive growth phase. The only significant interaction between day and night temperatures for the yield components was for seed weight per plant during flowering and pod set. Night temperature stress did not occur at 30°C, and a night temperature of 20°C did not reduce the yield loss from daytime high temperature stress. This study suggests that soybean seed yield reductions from high temperatures are primarily a response to day temperature, and moderate to high night temperatures have a small effect on soybean seed yield components (Gibson and Mullen, 1996).

Brown (1960) reported that the maximum rate of development between planting and flowering occurred at 30°C. Soybean plants are the most sensitive of all crop plants to light duration (photoperiod) and are sensitive to light quantity. They are short-day plants, but cultivars differ markedly with respect to the minimum dark period required to induce flowering (Chapman and Carter, 1976).

The water requirements of soybean vary with soil, climatic conditions, growth duration, and yield level. The total water requirement for soybean grown in the Midwestern United States has been reported to be in the range of 330–766 mm (Kanemasu et al., 1976; Musick et al., 1976). Water use for soybean can vary from 450 to 825 mm where the growing season ranges from 100 days at low altitude and up to 190 days in higher altitudes (Doorenbos and Pruit, 1977). Total water requirement for soybean in New South Wales (Australia) ranged from 451 to 748 mm per growing season (Mason et al., 1981). The water use pattern during crop growth in the Midwestern United States is shown in Figure 12.1. A description of growth stages V_1–R_8 corresponding to those described by Fehr et al. (1971) is presented in Section 12.3.4. The water requirement for soybean was low during the seedling and maturity stages and maximum during the flowering to seed-filling growth stages (Figure 12.1). This pattern of water uptake for soybean can be applied universally, but the magnitude may vary according to local conditions. In addition, genetic variability in water-use efficiency has been found in cultivars and lines of soybean (Mian et al., 1996, 1998; Hufstetler et al., 2007).

Soybean can extend its root system and extract soil water to a soil depth of more than 1.5 m (Reicosky and Deaton, 1979). Typical patterns of water use and root distribution during the growing season is given in Figure 12.1. Hiler et al. (1974) developed a water stress index for soybean during different growth stages based on yield reduction. To avoid stress, irrigation is needed when the soil

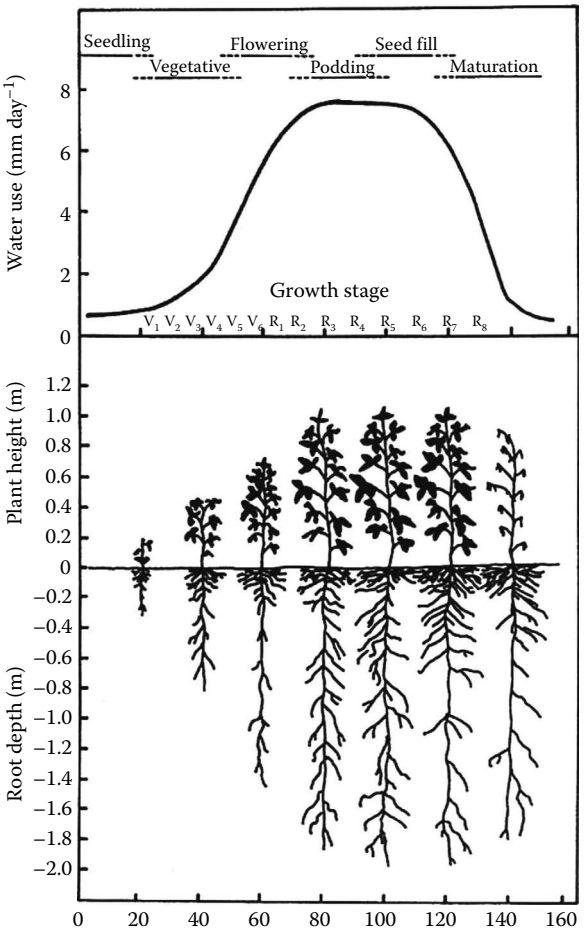

FIGURE 12.1 Seasonal water use and growth patterns of soybean. (From Van Doren, D.M. Jr. and Reicosky, D.C., Tillage and irrigation, in *Soybeans: Improvement, Production, and Uses*, 2nd edn, Wilcox, J.R. (ed.), *Agronomy Monograph*, 16, American Society of Agronomy, Madison, WI, 391–428, 1987. With permission.)

water depletion reaches 80% in the vegetative stage, 45% in early to peak flowering, 30% in late flowering to early pod development, and 80% in late pod to maturity. According to Brady et al. (1974), the best yields and most efficient water use are generally obtained when the available soil water in the root zone is not depleted by more than 50%–60%.

Yield decreases resulting from drought stress depend on both the phenological timing of the stress and the degree of yield component compensation (Pedersen and Lauer, 2004). Schou et al. (1978) reported that yield is more influenced by changes from flowering to physiological maturity compared with the emergence to flowering period. It is also reported by a number of researchers that the negative effects of water stress are particularly important during flowering, seed set, and seed filling where stress can reduce yield by reducing the number of pods, number of seeds, and seed mass (Ashley and Ethridge, 1978; Pedersen and Lauer, 2004).

Research on soybean irrigated by providing either permanent water surrounding raised beds or continuously running water between beds has shown that such regimes can increase yields by 10%–20% compared to conventional irrigation practices (Nathanson et al., 1984; Troedson et al., 1986). Termed "saturated soil culture" (SSC), this practice also increased N_2-fixation and delayed maturity (Nathanson et al., 1984; Troedson et al., 1989). Studies of water relations, photosynthesis, and nitrogen supply further suggested that the effects reflected improved crop water status (Troedson et al., 1989). In one study, no effect of SSC on seed yield was found, but N_2-fixation did increase (Wang et al., 1993). Comparison of two soybean lines differing in growth duration indicated that SSC was only effective for the line with a longer duration (Nathanson et al., 1984).

Symbiotic N_2 fixation is critical for obtaining high yields in soybean grown on soils without large amounts of available N (Cooper and Jeffers, 1984). The nitrogen fixation process of soybean is more sensitive to drought stress than other processes like transpiration, photosynthesis, and uptake and assimilation of inorganic soil N (Durand et al., 1987; Sall and Sinclair, 1991). Cox and Jolliff (1986) reported that leaf area index (LAI) and net assimilation rate (NAR) of soybean were reduced by drought stress. Pod number was the yield component most sensitive to drought, and yield was most sensitive to water stress during the podfilling period (Momen et al., 1979). The basis for the sensitivity of soybean to drought has been shown to be associated with transport of N as ureides from the nodules to the shoot (Sinclair et al., 2007). Soybean accumulates ureides during soil drying, affecting N_2 fixation activity (Serraj et al., 1999). Species that transport N as amides have less drought-sensitive N_2 fixation than those that transport ureides (Sinclair and Serraj, 1995).

Soybean can be grown on a wide range of well-drained soils but thrives best on clay loam soils. The crop is better adapted than either corn or cotton for production on clay soils. The crop is also suited for production on muck soils. The optimum soil pH for soybean production is in the range of 6–6.5 (Carter and Hartwig, 1962; McLean and Brown, 1984); however, significant genotypic variation in response to soil pH has been reported (Reddy and Dunn, 1987). Soybean often shows symptoms of iron deficiency chlorosis on calcareous soils with high pH (Rogovska et al., 2007). Rogovska et al. (2007) reported that soybean yield decreased when soil pH (in water) increased from about 6 to 8, and soil pH and cation exchange capacity explained 30% and 41% of the variability in relative yield across sites, respectively. Similarly, Bianchini and Mallarino (2002) and Sawyer et al. (2002) reported that no lime application is recommended for soybean when soil pH is higher than 5.9 in soils with calcareous subsoils. For soils without calcareous subsoils, lime should be applied if the pH is less than 6.4.

Availability of most micronutrients (except molybdenum) decreased with increasing soil pH. Among micronutrients, iron (Fe) deficiency chlorosis is very common in higher pH calcareous soils in various soybean growing regions of the world (Wiersma, 2005; Schenkeveld et al., 2008). Iron deficiency chlorosis reduces total soybean production in the United States by several million metric tones each year (Naeve and Rehm, 2006). As soybean production has expanded throughout high pH regions of North Central United States, the scope of this problem has grown. Several factors have been proposed as contributors to iron deficiency chlorosis, including soil carbonates (Morris et al., 1990), the ionic strength of the soil solution (as measured by electrical conductivity) (Morris et al., 1990; Franzen and Richardson, 2000), Fe oxide concentrations in the soil (Morris et al., 1990), diethylenetriamine-pentaacetate

TABLE 12.1
Yield of Selected Soybean Varieties Grown in Soils with 67% and 7% Al Saturation near Yurimaguas, Peru

Variety	Yield (Mg ha^{-1})		Relative Grain Yield
	Unlimed Soil	Limed Soil	
Hardee	1.23	2.13	58
SJ-2	1.20	2.07	58
Mineira	0.93	1.70	55
Jupiter	0.93	2.23	42
Improved Pelican	0.76	2.20	35

Source: Nicholaides, J.J. and Piha, M.I., A new methodology to select cultivars tolerant to aluminum and with high yield potential, in *Sorghum for Acid Soils*: *Proceedings of a Workshop on Evaluating Sorghum for Tolerance to Al Toxic Tropical Soils in Latin America*, *held in Cali, Colombia*, CIAT (ed.), May 28–June 2, 1984, Cali, Colombia, OH, 103–116, 1987.

(DTPA)-extractable Fe, chromium (Cr) concentrations, soluble salts, and soil water contents (Hansen et al., 2003, 2004). Several management practices have been proposed to reduce the severity of iron deficiency chlorosis, including foliar sprays of Fe (Goos and Johnson, 2000), Fe seed treatments (Wiersma, 2005), and increasing seeding rates (Goos and Johnson, 2000). All these management practices have shown limited usefulness in correcting iron chlorosis. Cultivar selection for iron use efficiency is the most desirable, effective, and environmentally sound strategy to minimize iron deficiency chlorosis in soybean grown on high pH calcareous soils (Goos and Johnson 2001; Hansen et al., 2003; Naeve and Rehm, 2006).

Soil Al concentration is an important component of soil acidity, and varietal differences in Al tolerance have been reported (Table 12.1).

Soybean is rated as a moderately salt-tolerant crop and the reported salinity threshold is about 5 dS m^{-1} (Maas, 1986; Chinnusamy et al., 2005). For example, salinity stress (6.7 dS m^{-1}) reduced the yield of soybean compared with low salt (0.8 dS m^{-1}) concentrations (Katerji et al. 2003). Salt damage in soybean results from the accumulation of chloride in stems and leaves, which causes leaf necrosis, reduces greenness in leaves, plant biomass, plant height, leaflet size, seed yield, seed quality, and seed emergence (Yang and Blanchar, 1993; An et al., 2002; Essa, 2002). However, salt tolerance differences among soybean genotypes are widely reported (Yang and Blanchar, 1993; An et al., 2001; Lee et al., 2008).

12.3 GROWTH AND DEVELOPMENT

Key growth stages used to describe soybean development are emergence, unifoliate (node of the first leaves), and trifoliate nodes (nodes of the second leaf to the last leaf on the main stem), flowering (R_1), full bloom (R_2), beginning pod (R_3), full pod (R_4), beginning seed (R_5), full seed (R_6), and physiological maturity (R_7) (Fehr and Caviness, 1977; Setiyono et al., 2008).

12.3.1 Germination and Seedling Growth

Germination can be defined as the emergence from the seed embryo of the essential structures needed to produce a normal plant under favorable conditions (USDA, 1952). Germination involves mobilization and utilization of food and energy reserves (Howell, 1960). Under favorable environmental conditions,

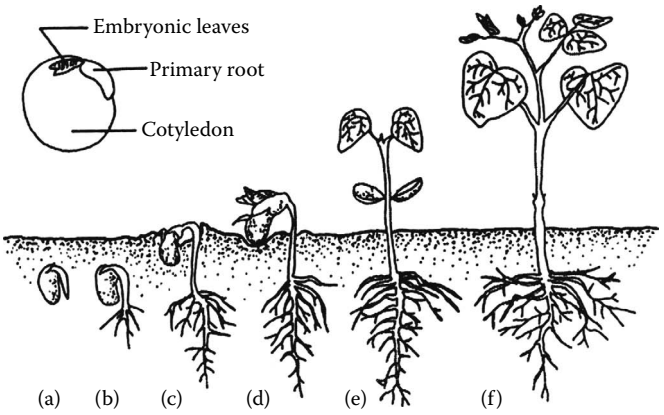

FIGURE 12.2 Germination and seedling development of soybean. Germination proceeds with the emergence of the radicle to form the primary root (a), development of secondary (branch) roots (b), and elongation of the active hypocotyl with the hypocotyl arch penetrating through the soil surface (c). Seedling becomes erect due to action of light on auxins (d), with cotyledons attached to the first node providing photosynthate in addition to stored energy for a short period of time (e), prior to drying and falling from the autotrophic seedling (f). Inset of enlarged seed with one cotyledon removed shows the primary root and embryonic leaves that develop into the first true leaves attached to the second node. (From Nelson, C.J. and Larson, K.L., Seedling growth, in *Physiological Basis of Crop Growth and Development*, Tesar, M.B. (ed.), American Society of Agronomy, Madison, WI, 93–129, 1984. With permission.)

seedlings begin to emerge in 4 or 5 days. Soybean germination is epigeal, like more than 90% of the dicot species, and the growing hypocotyl pulls the cotyledons above the ground (Nelson and Larson, 1984). Environmental factors that affect germination are soil moisture, temperature, and oxygen supply. A moisture content of about 50% is required for germination of soybean seed, and soybean fails to germinate if the soil moisture tension exceeds 6.6 atm (669 kPa). The optimum germination temperature is around 30°C–35°C. Temperature below that optimum delays germination (Bastidas et al., 2008). The germination and early seedling development stages are shown in Figure 12.2.

12.3.2 Vegetative Development

The important organs produced during vegetative development are roots, leaves, and stem. Vegetative development begins with the emergence of the young seedling from the soil surface and ends with the start of flowering. The vegetative growth supports the photosynthetic capacity of the plant, which supports the yield.

During vegetative growth, roots, leaves, and stems may compete for photosynthetic products. The partitioning of products is controlled by plant hormones and environmental factors. Water stress affects plant shoots more than roots. If soil temperature is more favorable for root growth than air temperature is for top growth, a greater percentage of dry matter may be diverted to root growth (Brown, 1984b).

12.3.2.1 Roots

Roots are important organs because they anchor the plant and supply water and mineral nutrients. The soybean root system is characterized by a taproot with lateral roots arising from the upper portion of the primary root. The soybean root system continues to grow throughout the life cycle of the plant except at physiological maturity, and the rate of root penetration is most rapid during early flowering (Kaspar et al., 1978). The majority of the root system is concentrated in the top 15 cm of the soil profile (Mitchell and Russell, 1971), but soybean roots have been observed as deep as 1.5–2 m below the soil surface under normal field conditions (Kaspar et al., 1984).

The rate at which plant root systems grow downward partly determines the water available for uptake, especially in a drying soil profile. Soybean cultivars differ in their rate of downward root

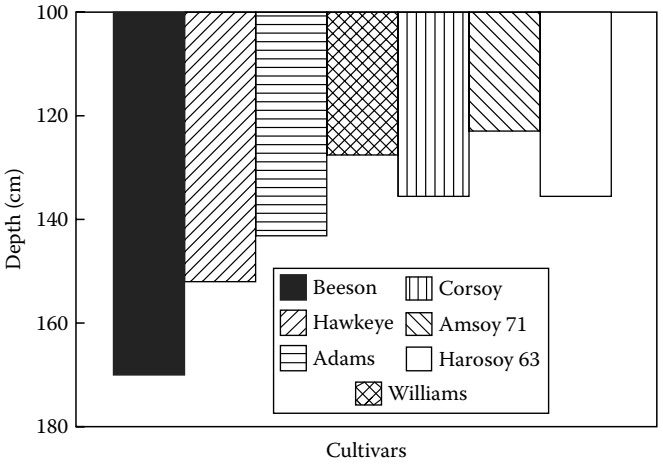

FIGURE 12.3 Differences in rooting depth of seven soybean cultivars. (From Klepper, B. and Kaspar, T.C., *Agron. J.*, 86, 745, 1994. With permission.)

growth and in their maximum rooting depth (Figure 12.3). Cultivars selected for rapid taproot elongation in a greenhouse trial were found to have greater rooting depths in rhizotron and field trials than cultivars selected for slow taproot elongation (Kaspar et al., 1984).

Four stages of soybean root development under field conditions have been reported: (1) rapid root growth beneath plant rows during the vegetative stage, (2) branching of roots during early reproductive growth, (3) decreased root growth beneath rows and increased root growth between rows during pod set, and (4) cessation of root growth and root loss due to decomposition during physiological maturity (Brown, 1984a; Hoogenboom et al., 1987a,b).

12.3.2.2 Nodulation

As a legume, soybean has the capacity to form a symbiotic association with *Bradyrhizobium japonicum* bacteria and fix atmospheric nitrogen. Many strains of this bacterium have been identified and some are more efficient than others (Whigham, 1983). When legume roots are infected by *Bradyrhizobium*, nodules are generally formed. Nodulation in legumes involves a series of biochemical interactions between the bacterium and the plant (Ciafardini and Barbieri, 1987). Bhuvaneswari et al. (1980) demonstrated that nodulation of soybean is limited to sites between the root tip and the smallest emergent root hair and does not occur on the walls of mature roots. Bergersen (1958) observed that nodules first appeared on Lincoln soybean 9 days after planting and N_2 fixation began about 2 weeks later. Nodules produced with the first infections on the primary root of soybean have an average duration of 65 days (Bergersen, 1958). Since reinfection of younger roots of soybean may occur during the growing season, a mature soybean plant may have nodules of several age classes. A chronology of nodulation in soybean is given by Lersten and Carlson (1987).

The quantity of N_2 fixed by soybean varies with environmental conditions and cultivar. In the early 1980s, Larue and Patterson (1981) concluded that no credible estimates of agricultural N_2 fixation were available for any legume crop. These authors reported soybean N_2 fixation values in the range of 15–162 kg N ha^{-1} in various countries. However, techniques for estimating N_2 fixation have improved, and Lindemann and Glover (2003) reported that up to 280 kg N ha^{-1}, accounting for 70% of total plant nitrogen requirement, can be fixed in soybean. Maximum N_2 fixation values of up to 360–450 kg N ha^{-1} have been suggested by several authors (Unkovich and Pate, 2000; Giller, 2001). For example, Salvagiotti et al. (2008) reported 337 kg N ha^{-1} as a reliable published maximum biological N_2 fixation value for soybean. The reason soybean is capable of fixing a large amount of nitrogen is the efficiency of the symbiosis between the plant root and *Bradyrhizobium japonicum*, the bacterial species specific to soybean nitrogen fixation (Balatti and Pueppke, 1992; Schulz and Thelen, 2008).

Total N uptake in soybean is generally measured in aboveground biomass near R_7 stage, when the soybean crop reaches maximum dry matter and N uptake (Salvagiotti et al., 2008).

Maximum N_2 fixation generally occurs between the R_3 and R_5 stages of soybean development (Zapata et al., 1987), and any gaps between crop N demand and N supply by N_2 fixation must be met by N uptake from other sources. Salvagiotti et al. (2008) reported that well-nodulated soybean crops that are without growth constraints and managed at yield levels above 4.5 Mg ha^{-1} are likely to respond to N fertilization. On average, 50%–60% of the soybean N demand is met by biological N_2 fixation across a wide range of yield levels and environments, and the proportion of plant N derived from fixation decreases with increasing inputs of N fertilizer (Salvagiotti et al., 2008). These authors also reported that in most situations the amount of N fixed by soybean is not enough to replace N export from the field with grain.

12.3.2.3 Top Growth

The soybean is an annual plant and usually grows to 75–175 cm in height (Shibles et al., 1975). Except at the cotyledonary and second nodes, the soybean has a single trifoliate leaf at each node. Soybean cultivars have two main growth habits: determinate and indeterminate. For cultivars with determinate growth, vegetative growth is nearly complete when the plant starts flowering. In the case of indeterminate growth, both vegetative and reproductive growth occur simultaneously after reproductive growth begins. Indeterminate soybean plants are taller and have more nodes, fewer pods, and smaller leaflets than determinate types (Whigham, 1983). Soybean plants increase in dry

TABLE 12.2
Chronology of Development of Flower and Ovule of Soybean[a]

Days before Flowering[a]	Morphological and Anatomical Features
25	Initiation of floral primordium in axil and bract.
25	Sepal differentiation.
20–14	Petal, stamen, and carpel initiation.
14–10	Ovule initiation; maturation of megasporocyte; meiosis; four megaspores present.
10–7	Anther initiation; male archesporial cells differentiate; meiosis; microsporogenesis.
7–6	Functional megaspore undergoes first mitotic division.
6–2	Second mitotic division results in four-nucleate embryo sac.
	Third mitotic division results in eight-nucleate embryo sac.
	Cell walls develop around antipodals and egg apparatus, forming a seven-celled and eight-nucleate embryo sac.
	Polar nuclei fuse. Antipodal cells begin to degenerate.
	Nucleus begins to disintegrate at micropylar end and on sides of embryo sac.
	Single vascular bundle in ovule extends from chalaza through funiculus and joins the carpellary bundle.
1	Embryo sac continues growth; antipodals disorganized and difficult to identify. Synergids with filiform apparatus; one synergid degenerating.
	Tapetum in anthers almost gone. Pollen grains mature; some are germinating.
	Nectary surrounding ovary reaches maximum height.
0	Flower opens; usually day of fertilization; resting zygote; primary endosperm nucleus begins dividing; nectary starts collapsing.

Source: From Carlson, J.B. and Lersten, N.R., Reproductive morphology, in *Soybeans: Improvement, Production, and Uses*, 2nd edn, Caldwell, B.E. (ed.), *Argonomy Monograph*, 16, American Society of Agronomy, Madison, WI, 95–134, 1987.

[a] The times are a compilation of data for several soybean cultivars studied by Kato et al. (1954), Murneek and Gomez (1936), Pamplin (1963), and Prakash and Chan (1976). The sequence of development is essentially the same regardless of cultivar, but the absolute times vary with environmental conditions and with cultivars.

weight slowly at first and then more rapidly (Rosolem, 1980). The dry weight of vegetative parts decreases during the latter part of grain development (Rosolem, 1980).

12.3.3 Reproductive Growth

The reproductive growth period is usually represented by flowering and pod and seed development. Initiation of flowering varies with genotype and environmental factors. Flowering may begin at 25 days or may be delayed until 50 days when certain genotypes and environments interact (Whigham, 1983). Pods are normally visible about 10 days to 2 weeks after the start of flowering (Howell, 1960). Soybean is a predominantly self-pollinating crop. Flowering may occur over 4–6 weeks, depending on the environment and the cultivar. After fertilization of the flower, the pods develop slowly for the first few days; then the rate of development increases until the pod reaches maximum length after 15–20 days (Whigham, 1983). The number of pods varies from 2 to more than 20 in a single inflorescence, and up to 400 pods may develop on a single plant (Carlson and Lersten, 1987). At maturity, pods usually contain 2–3 seeds but can contain as many as five. Seeds may vary in shape from nearly spherical to somewhat flattened disks and in color from pale green and yellow to dark brown (Chapman and Carter, 1976). A chronology of the development of flowers, pods, and seeds is presented in Tables 12.2 and 12.3. The data presented in these tables were compiled by Carlson and Lersten (1987) from several sources. According to these authors, the sequence of events remains the

TABLE 12.3
Chronology of Development of Seed and Pod of Soybean[a]

Days after Flowering	Morphological and Anatomical Features
0	Resting zygote. Several divisions of primary endosperm nucleus.
1	Two-celled proembryo. Endosperm with about 20 free nuclei.
2	Four- to eight-celled proembryo.
3	Differentiation into proembryo proper and suspensor. Endosperm in peripheral layer with large central vacuole.
4–5	Spherical embryo with protoderm and large suspensor. Endosperm surrounding embryo is cellular but elsewhere it is mostly acellular and vacuolate.
6–7	Initiation of cotyledons. Endosperm mostly cellular.
8–10	Rotation of cotyledons begins. Procambium appears in cotyledons and embryo axis. All tissue systems of hypocotyl present. Root cap present over root initials. Endosperm all cellular.
10–14	Cotyledons have finished rotation and are in normal position with inner surfaces or cotyledons parallel with sides of ovules.
	Cotyledons elongate toward chalazal end of ovule. Primary leaf primordia present. Endosperm occupies about half of seed cavity. Extensive vascularization of seed coat.
14–20	Continued growth of embryo and seed. Reduction in endosperm tissue by assimilation into cotyledons.
20–30	Primary leaves reach full size. Primordium of first trifoliate leaf present. Cotyledons reach maximum size. Endosperm almost gone.
30–50	Continued accumulation of dry matter and loss in fresh weight of seeds and pod. Maturation of pod.
50–80	Various maturity times depending on variety and environmental factors.

Source: From Carlson, J.B. and Lersten, N.R., Reproductive morphology, in *Soybeans: Improvement, Production, and Uses*, 2nd edn, Caldwell, B.E. (ed.), *Argonomy Monograph*, 16, American Society of Agronomy, Madison, WI, 95–134, 1987.

[a] The times are a compilation of data for several soybean cultivars studied by Bils and Howell (1963), Fukui and Gotoh (1962), Meng-Yuan (1963), Kamata (1952), Kato et al. (1955), Ozaki et al. (1956), Pamplin (1963), and Suetsugu et al. (1962). The sequence of development is essentially the same regardless of cultivar, but the absolute times vary with environmental conditions and with cultivars.

TABLE 12.4
Description of Vegetative and Reproductive Growth Stages in Soybean

Growth Stages	Description
Vegetative (V)	
V_1	Completely unrolled leaf at the unifoliate node.
V_2	Completely unrolled leaf at the first node above the unifoliate node.
V_3	Three nodes on main stem beginning with the unifoliate node.
V(*N*)	*N* nodes on the main stem beginning with the unifoliate node.
Reproductive (R)	
R_1	One flower at any node.
R_2	Flower at node immediately below the uppermost node with a completely unrolled leaf.
R_3	Pod 0.5 cm long at one of the four uppermost nodes with a completely unrolled leaf.
R_4	Pod 2 cm long at one of the four uppermost nodes with a completely unrolled leaf.
R_5	Seeds beginning to develop (can be felt when the pod is squeezed) at one of the four uppermost nodes with a completely unrolled leaf.
R_6	Pod containing full-size green seeds at one of the four uppermost nodes with a completely unrolled leaf.
R_7	Pods yellowing; 50% of leaves yellow. Physiological maturity.
R_8	95% of pods brown. Harvest maturity.

Source: Fehr, W.R. et al., *Crop Sci*., 11, 929, 1971. With permission.

same regardless of cultivar or environmental conditions, but the absolute times between events may vary by several days as a function of cultivar and environment.

12.3.4 Vegetative and Reproductive Growth Stages

The vegetative and reproductive growth stages of soybean were described by Fehr et al. (1971) and apply to all soybean genotypes grown in any environment. Vegetative (V) stages are designated by the number of nodes on the main stem, beginning with the unifoliate node that has or has had a completely unrolled leaf. Reproductive stages R_1 and R_2 correspond to flowering, R_3 and R_4 to pod development, R_5 and R_6 to seed development, and R_7 and R_8 to maturation. A detailed description of these growth stages is presented in Table 12.4.

12.4 YIELD COMPONENTS

Yield of a grain crop is the product of interaction between genotypes and environment (Liu and Herbert, 2000). Cultivars capable of producing high seed yield in highly productive environments should possess vertical leaf orientation, high photosynthetic capacity, dark green leaves, and a short, stout stem that terminates growth early enough to allow maximum seed production capacity, with minimum interplant competition (Board and Tan, 1995; Ma et al., 2001; Ustun et al., 2001; Liu et al., 2005).

Soybean yield per unit area is the product of plants per unit area, pods per plant, seeds per pod, and mass per seed, expressed mathematically by the following equation (Ball et al., 2001):

$$\text{Mass seed m}^{-2} = (\text{Plants m}^{-2}) \times (\text{Pods plant}^{-1}) \times (\text{Seeds pod}^{-1}) \times (\text{Mass seed}^{-1})$$

Pod number is determined by pods per reproductive node and the number of reproductive nodes. All these yield components are determined at different stages of reproductive growth (Egli, 1993; Board and Tan, 1995). The number of pods per reproductive node is determined by the difference between

total pods per reproductive node initiated (pods at least 0.5 cm long) and those aborted (Fehr and Caviness, 1977). Reproductive node number is determined by total node number and the percentage of nodes that become reproductive (percentage reproductive nodes). Although main stem node number in determinate cultivars is determined during the vegetative period, all other yield components contributing to pod number are determined during R_1–R_5. Seed number per unit land area is the most important yield component, and there is a differential response of yield components to changing environmental conditions (Herbert and Litchfield, 1982; Liu et al., 2005).

Pods plant^{-1} can be further divided into two components, fertile-nodes plant^{-1} and pods fertile-node^{-1}. The full soybean yield equation in multiplicative form is, therefore, as follows:

$$\text{Mass seed m}^{-2} = (\text{Plants m}^{-2}) \times (\text{Fertile-nodes plant}^{-1}) \times (\text{Pods fertile-node}^{-1}) \times (\text{Seed pod}^{-1}) \times (\text{Mass seed}^{-1})$$

Ball et al. (2001) reported that path analysis could be used to partition the relative contributions of yield components via standardized partial-regression coefficients. The correlation coefficients can be separated into the direct and indirect influences that one variable has on another (Dewey and Lu, 1959). Path analyses have been used to identify important yield components in various crops including soybean (Board et al., 1999; Shukla et al., 1999).

All yield components are influenced by environmental conditions, management practices, and the cultivar planted. Maximum grain yields have been reported for plant populations ranging from 200,000 plants ha^{-1} to more than 600,000 plants ha^{-1} (Whigham, 1983). Hiebsch et al. (1995) studied the relationships among plant density, soybean yield, and dry matter production of two cultivars (Figure 12.4). Optimum density was the same for seed yield (SY) and aboveground total dry matter yield (TY) for each soybean cultivar. The density producing 95% of maximum yield was 15 plants m^{-2} for the Cobb cultivar and 20 plants m^{-2} for the Davis cultivar.

The number of pods per plant varies according to growth habit, and determinate types typically produce more pods than indeterminate types. Flower and pod abortion may range from 40% to 80%, and ovule or seed abortion after pod development may occur at a rate of 9%–22% (Whigham, 1983).

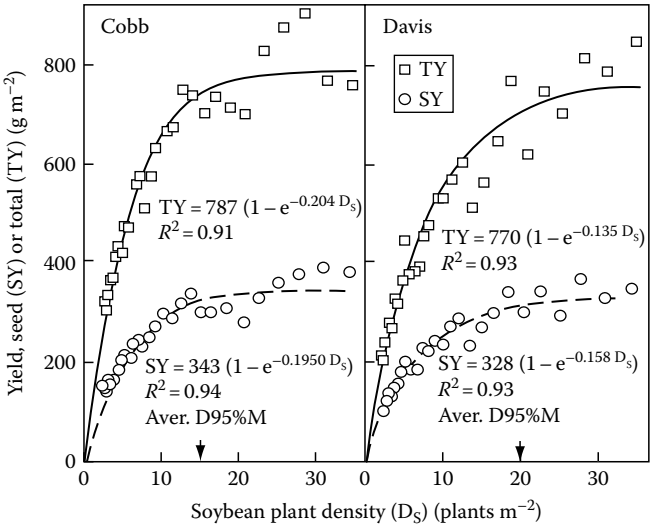

FIGURE 12.4 Seed yield and total dry matter yield of Cobb and Davis soybean cultivars as a function of soybean plant density. Arrows on the *X*-axes indicate the density for seed yield (SY) and aboveground total dry matter (TY) at 95% of maximum yield (D 95% M). (From Hiebsch, C.K. et al., *Agron. J.*, 87, 965, 1995. With permission.)

High abortion rates can be caused by long photoperiods, high or low temperatures, or light stress. Seed size, measured as mass per seed, is an important yield component in soybean and other grain crops (Egli et al., 1987). Seed size in soybean is under genetic control, and genotypes are available with sizes ranging from 40 to 550 mg seed^{-1} (Hartwig, 1973).

Seed size is also affected by environmental conditions during seed development (Shibles et al., 1975; Pedersen and Lauer, 2004). Seeds in pods developing from flowers that open early in the flowering period are larger than seeds in pods developing from flowers that open late in the flowering period (Egli et al., 1978; Gbikpi and Crooksten, 1981). Similarly, Spaeth et al. (1984) reported that seeds from lower nodes are larger than seeds from the upper nodes on the main stem. These variations in seed size were related to variation in duration of seed fill resulting from differences in the time of beginning of seed growth coupled with a relatively constant time of physiological maturity (Egli et al., 1987).

Pedersen and Lauer (2004) reported that grain yield of soybean were highly correlated with seed mass and grain harvest index. Management systems (conventional or no-till, with or without irrigation), planting date and cultivar influenced the development of the different yield components. For example, in their studies, seed mass ranged from 10.5 to 16.5 g 100 seed^{-1}, seed number from 2878 to 3824 seeds m^{-2}, pod number from 1182 to 1571 pods m^{-2}, and seeds per pod from 2.36 to 2.49 seeds pod^{-1}. Grain harvest index ranged from 0.56 to 0.58 across management systems.

12.5 MAJOR YIELD-DETERMINING PHYSIOLOGICAL PARAMETERS

Important physiological parameters that are directly related to yield include dry matter production, crop growth rate, leaf area index (LAI), net assimilation rate, and harvest index. A brief discussion of these parameters is given in this section.

12.5.1 Dry Matter

Improving dry matter accumulation is fundamental for increasing soybean yield (Specht et al., 1999). Liu et al. (2005) reported that high-yielding soybean genotypes not only accumulate dry matter linearly during reproductive period but also accumulate more dry matter and have higher leaf area index and leaf area duration than low-yielding genotypes. The accumulation of dry matter after the R_2 growth stage is an important factor in attaining high yields (Koutroubas et al., 1998). Significant higher dry matter in high-yielding cultivars after pod filling was also reported by Kumudini et al. (2001).

Accumulation of plant dry matter is a result of net CO_2 exchange between a crop and the atmosphere. Measurements of crop net CO_2 exchange rates (CNCER) are therefore useful in analyzing the physiological processes associated with plant growth and productivity and to validate crop growth models (Bugbee and Monje, 1992); CNCER (measured in mg m^{-2} s^{-1}) can be defined as (Rochette et al., 1995)

$$\text{CNCER} = P_{gc} - R_r - R_{ag}$$

where

P_{gc} is the gross crop photosynthesis

$R_r - R_{ag}$ are the respiration rates of the roots and aboveground parts of the crop, respectively

CNCER is considered positive when the crop is gaining *C*. CNCER cannot be measured directly under field conditions, but vertical CO_2 fluxes can be measured above the canopy ($F_{c,a}$) and at the soil surface ($F_{c,s}$):

$$C_{c,a} = -P_{gc} + R_r + R_{ag} + R_\mu$$

$$F_{cs} = R_\mu + R_r$$

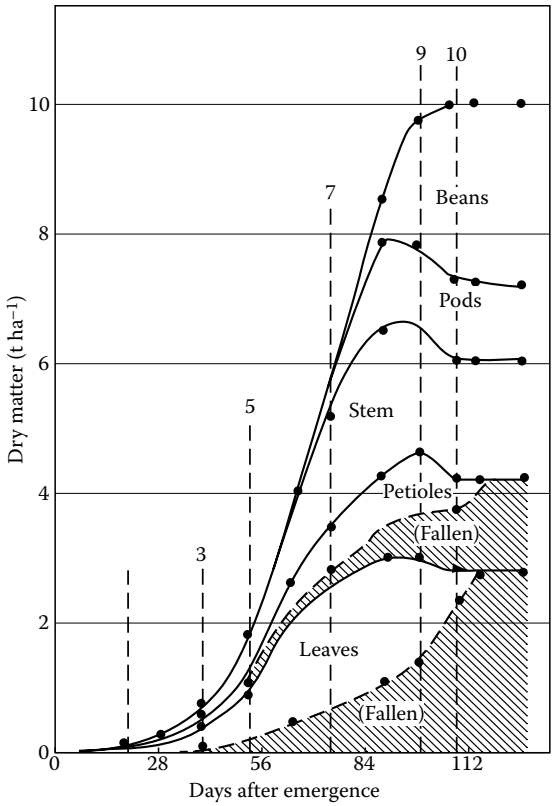

FIGURE 12.5 Dry matter accumulation of soybean plant parts at various stages of growth. (From Hanway, J.J. and Weber, C.R., *Agron. J.*, 63, 263, 1971a. With permission.)

where R_μ is the amount of $F_{c,s}$ that originates from respiratory activity of the soil fauna and flora. $F_{c,a}$ and $F_{c,s}$ are considered negative when fluxes are toward the field surface. Maximum daytime and minimum nighttime hourly values of CNCER were 1.48 and −0.23 mg m^{-2} s^{-1}, respectively (Rochette et al., 1995).

Soybean dry matter production is a function of environmental factors, cultivar planted, and management practices adopted. Figure 12.5 illustrates the cumulative dry weight of different plant parts at progressive stages of plant development (Hanway and Weber, 1971a). Plant dry weight increased at an increasing rate until stages 3–5. After stage 5, the plant dry weight increased at a constant daily rate until stage 9 late in the season. Stem and pod dry weights declined during the late stages of seed filling as tissue lost dry matter because of respiration and mobilization to the seed. At maturity, dry matter consisted of 28% fallen leaves, 15% fallen petioles, 17% stems, 11% pods, and 29% seeds.

Figure 12.6 shows the influence of water on dry matter production of soybean. The deficit irrigation and dryland treatments produced significantly less dry matter (18% and 70%, respectively) than the well irrigated treatment (Cox and Jolliff, 1986). A detailed discussion of the distribution of dry matter in different plant parts of soybean is given by Shibles et al. (1987).

12.5.2 Crop Growth Rate

Crop growth rate is related to light interception by the crop canopy, and the leaf area index that produces 95% light interception ranges from 3.1 to 4.5, depending on planting density and spatial arrangement (Shibles and Weber, 1966). The highest crop growth rate reported for irrigated

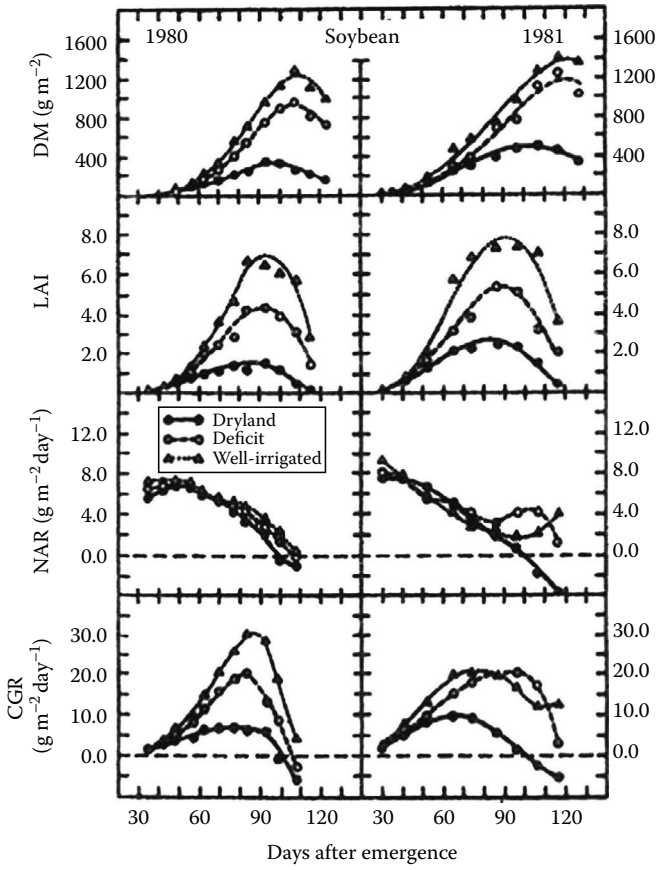

FIGURE 12.6 Seasonal patterns of total dry matter production (DM), leaf area index (LAI), net assimilation rate (NAR), and crop growth rate (CGR) in well-irrigated, deficit, and dryland treatments of soybean. (From Cox, W.J. and Jolliff, G.D., *Agron. J.*, 78, 226, 1986. With permission.)

soybeans is 30 g m^{-2} day^{-1} (Cox and Jolliff, 1986). Figure 12.6 shows that irrigation can have a significant effect on crop growth rate of soybean.

12.5.3 Leaf Area Index

Leaf area index (LAI) is defined as the area of leaf surface per unit area of land surface. Leaf area is critical for crop light interception and therefore has a substantial influence on crop yield (Loomis and Connor, 1992; Evans, 1996; Kakiuchi and Kobata, 2004; Liu et al., 2005). Soybean yield is positively related to LAI at the R_5 stage (Board and Tan, 1995; Kumudini, 2002). Maximum LAI values may range from 5 to 8 in soybean (Whigham, 1983). Maximum leaf area production for determinate cultivars may occur near the beginning of flowering, but indeterminate cultivars reach a maximum leaf area near the end of flowering. Shibles and Weber (1965) reported that an LAI of 3.2 was required for 95% light interception and 95% dry matter production. Defoliation studies conducted during the first half of the seed filling period demonstrated that yield was reduced only when defoliation was severe enough to reduce LAI below about 3.5, a level at which light interception started falling below the optimal 95% level (Board and Harville, 1993; Board and Tan, 1995; Board et al., 1997; Board, 2004). It was therefore concluded that either maintenance of an LAI of 3.5–4.0 and/or light interception of 95% could be used as a criterion for identifying areas experiencing injury by defoliation pests (Board et al., 2007). Similarly, Highly (2001) proposed using

LAI to estimate economic losses due to pests. Figure 12.6 shows the LAI of soybean at different growth stages and the influence of irrigation treatments on LAI.

12.5.4 Net Assimilation Rate

A useful measure of the photosynthetic efficiency of plants is net assimilation rate (NAR), defined as the rate of increase of dry matter per unit of leaf area. The NAR is generally constant in the beginning of crop growth and then decreases (Figure 12.6). As LAI increases, photosynthetic efficiency per unit leaf area is reduced as a result of competition for light, and NAR decreases. Another reason for NAR decrease is leaf senescence as the crop approaches maturity (Clawson et al., 1986).

12.5.5 Grain Harvest Index

The grain harvest index, defined as the ratio of grain to total dry matter production in crops, is used as an index of dry matter distribution within the crop. It is now well established that the increased grain yields of improved cultivars over the last several decades has been more the result of increased partitioning of dry matter to grain rather than to increased biomass production (Gifford and Evans, 1981; Fageria, 2009). In soybeans, competition among plant parts for photosynthetic products varies during the growth cycle. Vegetative plant parts are the only sinks for assimilate prior to flowering, and during flowering and fruit set, vegetative and reproductive plant parts are competing sinks for assimilate. The fruit is the primary sink for assimilate during the seed-filling period (Egli, 1988).

Grain harvest index of a cultivar is often considered a relatively stable characteristic that varies little with environmental conditions (Spaeth et al., 1984). However, Johnson and Major (1979) reported that grain harvest index for soybeans varied from 0.30 to 0.40, depending on the maturity of the cultivars and production practices. Kakiuchi and Kobata (2004) reported that grain harvest index of soybean varied from 0.37 to 0.43 and may be unstable when shoot dry matter is markedly affected by variation in environmental conditions such as solar radiation. Similarly, Liu et al. (2005) reported that the grain harvest index of soybean varied from 0.49 to 0.57 depending on yield potential and maturity group. Grain harvest index of modern soybean cultivars is higher compared to older cultivars.

12.6 NUTRIENT REQUIREMENTS

Nutrient requirements of a crop vary according to soil and climatic conditions, cultivar, yield level, cropping system, and management practices. Further, the quantity of fertilizer applied by farmers varies with the socioeconomic situation. Therefore, it is not possible to make fertilizer recommendations that are universally applicable. Basic principles of nutrient requirements of soybeans are discussed in this section and can be used as guidelines for fertilization.

Soybeans can fix atmospheric N if the proper strain of *Bradyrhizobium* bacteria is present in the soil or if the seed is properly inoculated. The plant starts to fix substantial amounts of atmospheric N approximately 4 weeks after germination. The amount of N_2 fixed depends on the climate, soil type, and variety grown (Ledgard and Steele, 1992). Most estimates show that soybean derives between 25% and 75% of its N from fixation (Deibert et al., 1979). The variable amount of N fixed by soybean is due to the several factors that affect fixation, including the length of time that a soybean variety actively supports N_2-fixation (Hardy, 1977). Higher levels of mineral N retard early nodule development, but under some conditions, marked beneficial effects of mineral nitrogen on the total amount of N_2 fixed during the growing season have been recorded (Shibles et al., 1975). Early supplies of mineral N enable the plant to maintain rapid early growth, stimulate photosynthesis and nodule development once the inhibition of soil mineral N ceases, and, because of the increased plant size, may increase nodule mass (Shibles et al., 1975).

Imsande (1992) related various N-dependent growth characteristics of soybean to seed yield and seed protein content. Twenty growth-yield characteristics, including yield, harvest index, N harvest

index, and Kjeldahl analysis of N_2 fixation, were measured or calculated for each of the 384 plants examined. The highest seed yields, approximately 10 g plant^{-1}, and the highest seed N contents, approximately 560 mg plant^{-1}, were obtained when well-nodulated plants were provided some fertilizer-N during pod fill. Except for N content (%) of the dried plant, correlations between each pair of the 20 N-dependent growth-yield characteristics were generally positive. In the absence of fertilizer-N during pod fill, however, N content (%) of the seeds did not correlate with either harvest index or N harvest index, suggesting that insufficient N during pod fill interferes with the orderly mobilization of foliar-N to the developing seeds. New physiological parameters (seed yield merit, N yield merit, and merit of genotype) are proposed for the identification of genetic lines that produce both a high seed yield and a high seed protein content (Imsande, 1992).

Soybean response to N fertilizer is inconsistent, unpredictable, and often unexplainable (Small and Ohlrogge, 1973). Conflicting effects of N application to soybean have been reported, from response to no response (Mengel et al., 1987). But soybean producers in the United States apply about 2–9 kg N ha^{-1} at planting, depending on the geographic region (Hargett and Berry, 1983). Similarly, in Brazil, which is the second largest producer of soybean, farmers apply about 10–20 kg N ha^{-1} at planting (Peter, 1980). Other essential nutrients such as P, K, Ca, Mg, and S and micronutrients should also be applied in appropriate amounts if soils are deficient in these nutrients.

Phosphorus deficiency is widespread in acid soils used for soybean production. An adequate level is generally applied on the basis of critical soil P level. Cox (1992) determined the critical levels of Mehlich-3 extractable P for soybean grown on a Typic Unbraquult. When the data were analyzed with the linear-plateau method, critical levels ranged from 33 to 39 mg P kg^{-1}, with a mean of 35 mg P kg^{-1}. However, when an exponential function was used to estimate 95% of maximum yield, the range of critical values was 55–82 mg kg^{-1} with a mean of 64 (Figure 12.7). Responses to P fertilizers were frequent when soils tested very low or low (<130 mg K kg^{-1} and <16 mg P kg^{-1} by Bray P_1 or Mehlich-3 tests, respectively) according to Iowa State University interpretations (Sawyer et al., 2002).

Crop response to K fertilization is often correlated with exchangeable K. In soils of the Cerrado region of Brazil, response to K fertilization is expected when the level of exchangeable K is less than 0.15 cmol kg^{-1}. Cox and Uribe (1992) determined soybean response to potassium in a tropical Ultisol. Critical exchangeable level was 75 kg ha^{-1} (37.5 mg K kg^{-1}) when K was extracted by $NaHCO_3$ extracting solution (Figure 12.8). Borkert et al. (1993) also determined soybean response to K fertilization in Brazilian Oxisol. Maximum grain yield was obtained at about 100 kg K ha^{-1} (Figure 12.9). These authors also calibrated a K soil test against soybean grain yield. Based upon the data of 5 years of experimentation, three classes of soil exchangeable potassium contents in the soil were defined: Low, when K content is less than 23 mg kg^{-1}; medium, when it is between 23 and 40 mg kg^{-1}; and high, when it is higher than 40 mg kg^{-1} by Mehlich-1 extracting solution (Borkert et al., 1993).

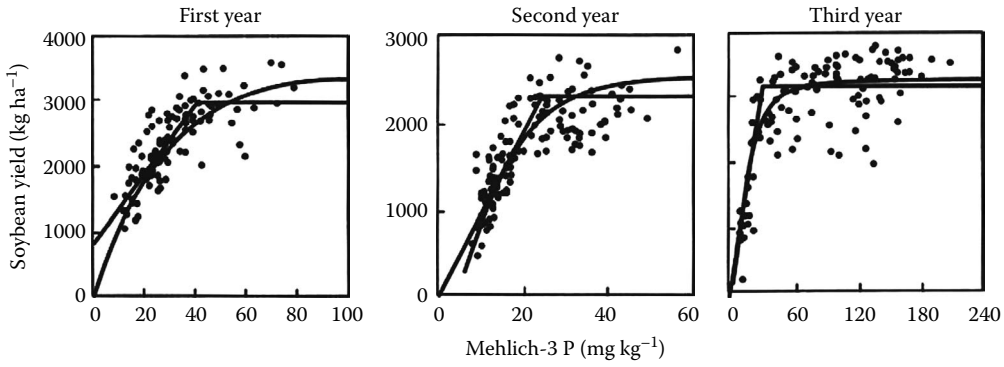

FIGURE 12.7 Response of soybean to Mehlich-3 P with linear-plateau and exponential prediction functions for three crops. (From Cox, F.R., *Soil Sci. Soc. Am. J.*, 56, 1504, 1992. With permission.)

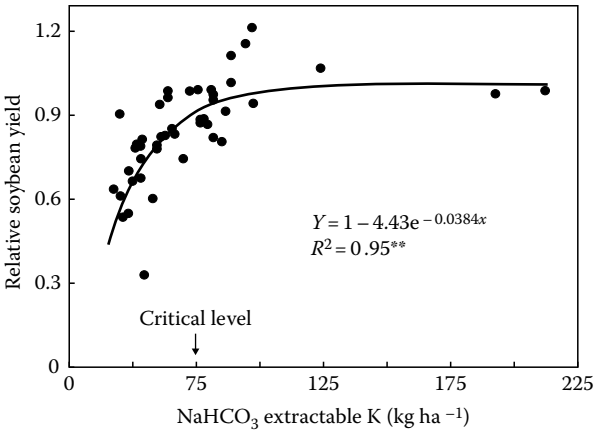

FIGURE 12.8 Relationship between $NaHCO_3$ extractable K and relative soybean yield, ** significant at the 1% probability level. (From Cox, F.R. and Uribe, E., *Agron. J.*, 84, 480, 1992. With permission.)

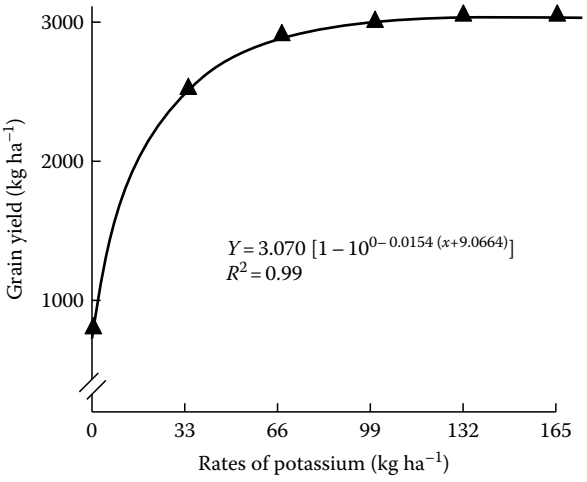

FIGURE 12.9 Relationship between soybean yield and rates of K applied as broadcast in an Oxisol. (From Borkert, C.M. et al., *R. Bras. Ci. Solo*, 17, 223, 1993.)

Galrão (1993) determined the critical zinc level in an Oxisol of central Brazil for soybean using three extracting solutions: 0.1 N HCl, Mehlich-1 (0.05 N HCl + 0.025 N H_2SO_4) and DTPA (diethylenetriaminepentaacetic acid). The critical Zn levels were 1.2, 0.8, and 0.6 mg kg^{-1}, respectively, by these three extracting solutions (Figure 12.10). Ross et al. (2006) reported that soybeans with low tissue B concentration (<20 mg B kg^{-1}) generally respond positively to B fertilization. These authors also reported that application of 0.28–1.12 kg B g ha^{-1} during early vegetative or reproductive growth was sufficient to produce near maximum yields. Much of the B fertilization research conducted with soybean has examined B fertilization for the purpose of increasing soybean yield potential by increasing yield components (Reinbott and Blevins, 1995), especially for soybean grown in high-yielding environments (Touchton et al., 1980).

12.6.1 Nutrient Concentration and Uptake

Information on nutrient concentration (content per unit dry matter) and uptake (concentration × dry matter) is important in understanding the mineral requirements of soybean. Nutrient concentration information is obtained through plant tissue analysis and can be used in the diagnosis of nutrient

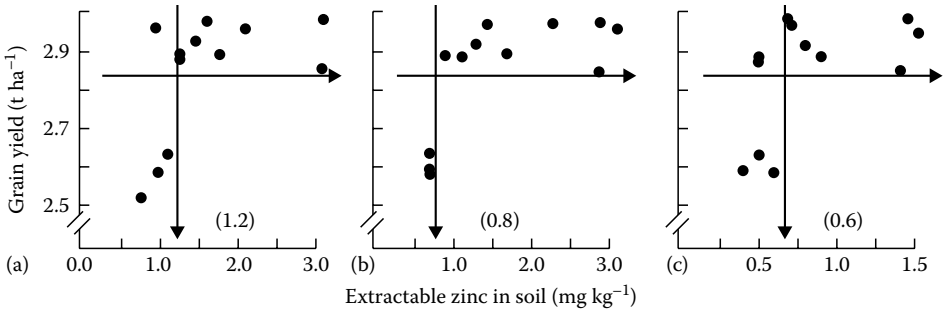

FIGURE 12.10 Relationship between soybean yield and extractable Zn in an Oxisol. Extractant of (a) = 0.1 N HCl, (b) = Mehlich-1, and (c) = DTPA. (From Galrão, E.Z., *R. Bras. Ci. Solo*, 17, 83, 1993.)

deficiency or sufficiency for crop production. Similarly, nutrient uptake data can be used to study nutrient removal from the soil in order to maintain or improve soil fertility.

Nutrient concentration and uptake of soybean vary with environmental conditions, cultivar planted, yield level, and management practices. The data presented in Table 12.5 for concentration and Table 12.6 for uptake provide guidelines for understanding the mineral requirements of the crop. Nutrient concentrations below the minimum and above the maximum are easy to interpret, but interpretations in the middle range are more difficult.

TABLE 12.5
Deficient, Sufficient, and High Concentrations of Nutrients for Upper Fully Developed Trifoliate Prior to Pod Set

	Deficient	Sufficient	High
Nutrient		**g kg^{-1}**	
N	40	45–55	56–70
P	1.5	2.6–5	6–8
K	12.5	17–25	26–28
Ca	2.0	3.6–20	21–30
Mg	1.0	2.6–10	11–15
S	—	2.5–4	—
		mg kg^{-1}	
Fe	30	51–350	351–500
Mn	14	21–100	101–250
Zn	10	21–50	51–75
B	10	21–55	56–80
Cu	4	10–30	31–50
Mo	0.4	1–5	6–10
Al	—	200	201–400

Sources: Small, H.G. and Ohlrogge, A.J., Plant analysis as an aid in fertilizing soybeans and peanuts, in *Soil Testing and Plant Analysis*, Walsh, L.M. and Beaton, J.D. (eds.), Soil Science Society of America, Madison, WI, 315–327, 1973; Rosolem, C.A., Mineral nutrition and fertilization of soybean, Tech. Bull. 6, Potassium and Phosphate Institute, Piracicaba, Brazil, 1980.

TABLE 12.6
Uptake of Macronutrients and Micronutrients in the Shoot and Grain of Soybean Grown on Brazilian Oxisol

Nutrient	Shoot (kg ha^{-1}) or (g ha^{-1})[a]	Grain ((kg ha^{-1}) or (g ha^{-1})[a]	Total (kg ha^{-1}) or (g ha^{-1})[a]	kg Nutrient Uptake in Grain and Shoot to Produce 1 Mg Grain[b]
Nitrogen	37.5	280.0	317.5	79
Phosphorus	1.76	14.3	16.1	4
Potassium	57.5	77.5	135.0	34
Calcium	31.0	13.4	44.4	11
Magnesium	20.3	10.2	30.5	8
Zinc	29.3	169.3	198.6	50
Copper	32.8	60.3	93.1	23
Manganese	117.4	120.1	237.5	59
Iron	187.3	373.0	560.3	140

Note: Grain yield was 4003 kg ha^{-1} and shoot dry weight was 3518 kg ha^{-1}.

[a] Macronutrients in kg ha^{-1} and micronutrients in g ha^{-1}.

[b] Total nutrient uptake was taken into account to calculate nutrient requirement per Mg grain.

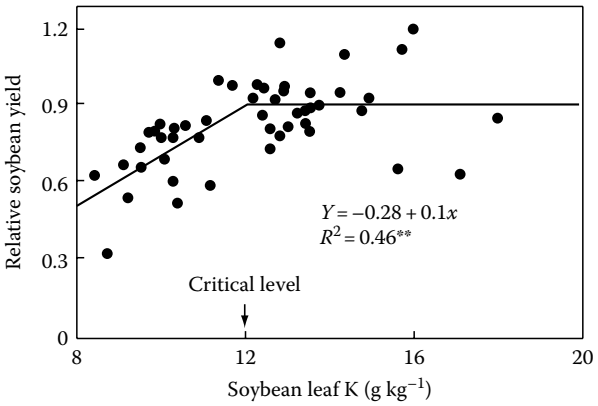

FIGURE 12.11 Relationship between K content of soybean leaf at flowering and relative grain yield, ** significant at the 1% probability level. (From Cox, F.R. and Uribe, E., *Agron. J.*, 84, 480, 1992. With permission.)

Cox and Uribe (1992) determined that 12 g K kg^{-1} of dry weight is a critical level the K in soybean leaf tissue at flowering (Figure 12.11). Manganese deficiency in soybean is frequently reported when the pH of acid soils is raised by liming (Gettier et al., 1985). Further pressure is placed upon soil Mn reserves by high yields and multiple cropping systems. Gettier et al. (1985) determined the critical Mn level in soybean plants. Based on 90% of maximum yield as the definition of the critical deficiency level, the critical Mn levels for whole plant, leaf, and seed were 45, 17, and 20 mg kg^{-1}, respectively. A relationship between leaf Mn concentration and percent maximum yield is presented in Figure 12.12.

Hanway and Weber (1971b) determined the relative uptake of N, P, and K by indeterminate soybean under field conditions. The relative amounts accumulated in different plant parts are presented in Figure 12.13. Total accumulation of N, P, and K in the plants followed patterns similar to that of dry matter accumulation. Accumulation was slow early in the growth stage but then became rapid, and nutrients accumulated at constant daily rates between stages 5 and 9. Approximately 80% of the total accumulation of these nutrients occurred during the 46 day period between stages 5 and 9.

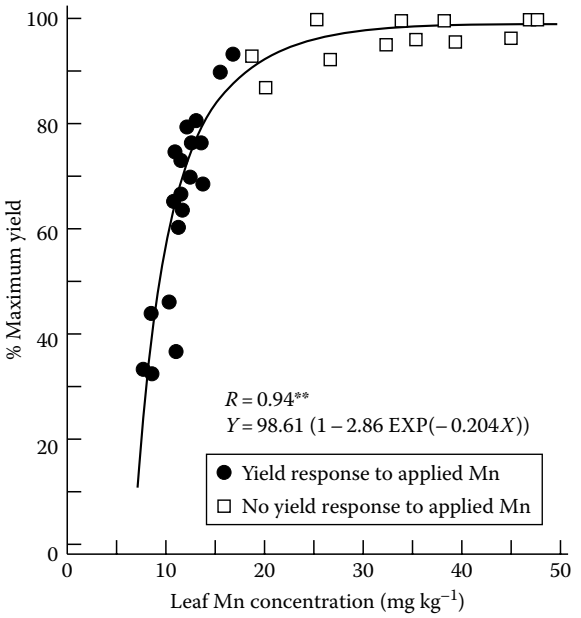

FIGURE 12.12 Soybean yield response curve for uppermost mature trifoliate leaf manganese concentrations sampled at early bloom, ** significant at the 1% probability level. (From Gettier, S.W. et al., *Agron. J.*, 77, 63, 1985. With permission.)

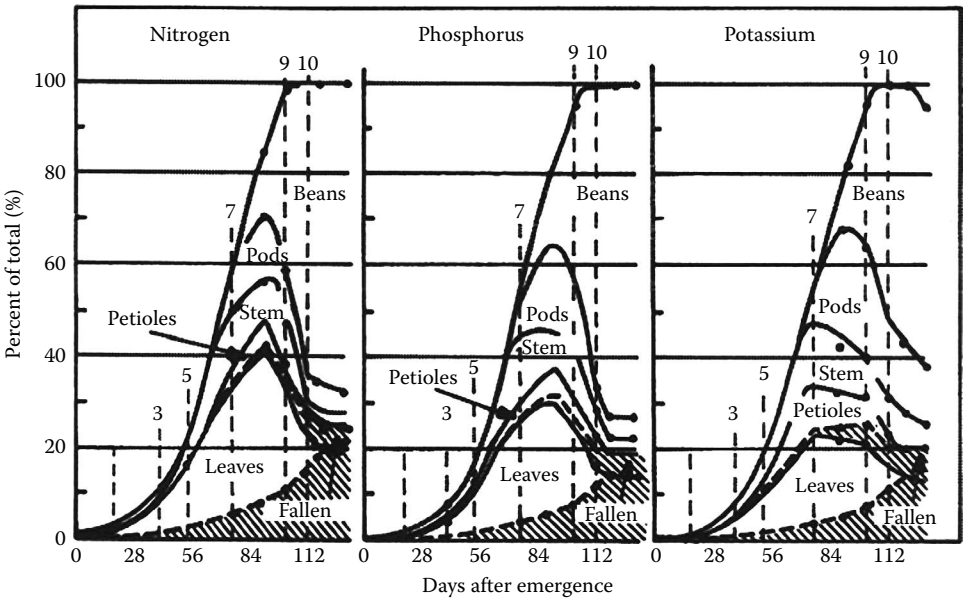

FIGURE 12.13 Relative amounts of N, P, and K in different plant parts of soybean at different growth stages. (From Hanway, J.J. and Weber, C.R., *Agron. J.*, 63, 406, 1971b. With permission.)

12.7 SUMMARY

Soybean is the most important oil and protein crop in the world. It is unique among edible legumes because it has high concentrations of both oil and protein. Soybean oil is used for cooking, to make margarine, and for a range of industrial products including paints, linoleum, inks, and soap. Once oil has been extracted from the seed, the residual protein cake is used to manufacture foods for animals

and humans. Soybean is the most important warm-season legume in temperate climates, and its use is growing in the tropics and subtropics. The species was probably domesticated in Northeastern China over 1000 years ago, and its adaptability has increased as cultivars with different degrees of photoperiod sensitivity, higher harvest index, and better disease resistance have been developed. Soybeans are grown from 0° to 55° latitude and from below sea level to 2000 m elevation, but most commercial production is between 25° and 45° latitude and below 1000 m elevation. Soybeans can be grown on a wide range of well-drained soils, and the optimum soil pH is reported to be 6.0–6.5. Soybean is moderately tolerant of salinity. The threshold salinity for soybean is 5.0 dS m^{-1}. Like most grain crops, it is most sensitive to water stress during flowering and early grain development. Soybean is often grown in rotation with warm-season cereals such as corn in order to facilitate pest control and optimize available labor.

Soybean has efficient symbiotic nitrogen fixation that can provide over 80% of the nitrogen in the crop at maturity; however, in most cases, fixation accounts for 25%–75% of total plant nitrogen. Nitrogen fixation begins after nodulation by appropriate strains of *Bradyrhizobium* (about 4 weeks after germination). Fixation is inhibited by high levels of mineral nitrogen in the soil, by drought stress, and by poor soil aeration. Though soybean's response to fertilizer N is inconsistent, small amounts are often applied at planting to stimulate plant growth until symbiotic nitrogen fixation begins.

To produce 1 metric ton of grain, soybean plants accumulated approximately 80 kg N, 4 kg P, and 34 kg K in grain and shoot. To maintain soil fertility, nutrients (other than nitrogen) removed in the grain should be returned in fertilizers and/or manures. Both soil and plant analyses can be used to detect nutrient deficiencies and toxicities.

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13 Common Bean and Cowpea

13.1 INTRODUCTION

Common bean (*Phaseouls vulgaris* L.) and cowpea (*Vigna unguiculata* L. Walp.) are important seed legume crops and supply a large part of the daily protein requirement of the people of South America, the Caribbean, Africa, and Asia. Common bean is a principal source of protein for more than 500 million people in Latin America and Africa; when consumed as snap beans, it is an important dietary source of vitamins and minerals in Asia (Yan et al., 1995; Fageria, 2002, 2006; Fageria et al., 2008). Common bean and cowpea seeds are rich in protein (20%–25%). Though their proteins are deficient in sulfur amino acids, they complement cereals and other carbohydrate rich foods in providing near-perfect nutrition to people of all ages. Moreover, a regular intake of beans helps lower cholesterol and cancer risks (Singh, 1999). Beans are also one of the best nonmeat sources of iron, providing 23%–30% of daily recommended levels from a single serving (Perla et al., 2003; Shimelis and Rakshit, 2004). Santalla et al. (2001) reported that common bean is potentially the most valuable source of plant protein for human consumption in many parts of South Europe and contributes significantly to the sustainability of traditional cropping systems.

Among major food legumes, dry bean is the third most important legume worldwide, superseded only by soybean and peanuts. Land area devoted to bean production in developing countries has increased steadily in the last several decades (CIAT, 1992). However, production has not kept pace with population growth and significant yield increases are required in Latin America and Africa to satisfy expected demand (Henry, 1989; Janssen, 1989; Fageria and Barbosa Filho, 2008). Bean production in developing countries is often on marginal land, and few developing countries have significant reserves of arable land that can be opened to bean cultivation, so increased bean production will largely have to come about through increased yield per hectare rather than expansion of area under cultivation.

Average bean yields in most developing countries are less than 20% of yield potential, indicating that substantial improvement in bean production could be realized by increasing yields per unit land area (Yan et al., 1995). For example, in Brazil average common bean yield is about 850 kg ha^{-1}. In contrast, experimental yields of more than 3000 kg ha^{-1} are frequently reported (Fageria, 2006, 2008; Fageria and Barbosa Filho, 2008; Fageria et al., 2008). Average yields of common bean are less than 1 Mg ha^{-1} in most developing countries and less than 1.5 Mg ha^{-1} in most developed countries (Laing et al., 1984; Fageria, 2006; Fageria and Barbosa Filho, 2008). Similarly, the average cowpea yield on a world level is about 400 kg ha^{-1} (Summerfield et al., 1983). The main reasons for low yields are water deficit, high incidence of diseases and insects, and limited use of inorganic fertilizers. Further, very little research has been devoted to improving productivity of these crops. Given the importance of bean and cowpea as human food sources, information related to soil and climatic requirements, physiology of crop yield, and mineral nutrition of these two crops is reviewed in this chapter.

13.2 COMMON BEAN

The common bean (*Phaseolus vulgaris* L.) is the most widely distributed and consumed legume species of *Phaseolus*, a genus composed of some 70 species (Debouck, 1991; Freytag and Debouck, 2002). Four other important species of *Phaseolus* are the runner bean (*P. coccineus* L.), the lima bean (*P. lunatus* L.), the year bean (*P.dumosus* Macfad), and the tepary bean (*P. acutifolius* A. Gray)

(Acosta-Gallegos et al., 2007). Among the five domesticated species, *Phaseolus vulgaris* L. accounts for more than 90% of the cultivated crop worldwide and is by far the most widely consumed seed legume in the world (Singh, 2001; Acosta-Gallegos et al., 2007). Common beans are also known as dry, field, French, snap, navy, or kidney beans. Beans are usually grown in tropical countries for dry seeds and in temperate countries for dry seeds as well as for fresh pod consumption and for processing as frozen vegetables (Singh, 1992, 1999). *Phaseolus vulgaris* is believed to have originated in Central America or South America. From its origin and initial domestication in Andean South and Middle America, common bean production and consumption expanded into other parts of the Americas (from about 35°S to >50°N latitude and from sea level to >3000 m latitude) (Singh, 1999). It was taken to Europe, Africa, and Asia in the sixteenth century by the Spanish and the Portuguese. Native Americans spread beans throughout North America, where they were grown in association with corn and squash. Numerous European cultivars were brought to the United States during the late nineteenth century (Evans, 1976). Miller et al. (2002) and Blackshaw et al. (2007) reported that production of pulse crops, including common bean, steadily increased over the last 2 decades on the Canadian prairies due to their rotational benefits and because they often provide greater economic return than cereals. *Phaseolus vulgaris* is now grown widely in many parts of the tropics, subtropics, and temperate regions (Purseglove, 1987; Singh, 1999). Maximum production of *P. vulgaris* is concentrated in South America and the Caribbean, followed by Africa, China, North America, and Europe (Laing et al., 1983; Pachico, 1989; Singh, 1999). Brazil and Mexico are the largest producers and consumers in the world.

In Africa, beans are produced by small-scale farmers with little use of inputs across a wide range of agro-ecosystems. Most common beans in Africa are produced as an intercrop with corn or as a sole crop, but intercrops with banana, root and tuber crops, sorghum, and millet are also practiced (Wortmann et al., 1998). The highest yearly per capita consumption (>40 kg) of dry bean is in Rwanda and Burundi (Centro Internacional de Agricultura Tropical, CIAT, 1981a), and it contributes as much as 30% of the dietary energy in the widespread maize-based cropping systems of eastern and southern Africa. The most important abiotic constraints are, N deficiency, and low soil pH associated with Al toxicity and P and Ca deficiencies. Major biotic constraints are angular leaf spot, anthracnose, bean stem maggot, bruchids, and root rots (Wortmann et al., 1998).

There are strong preferences for specific seed types of dry bean in different countries and regions within countries (Vieira, 1988; Voysest, 1989; Voysest and Dessert, 1991; Singh, 1999). In Brazil, for example, small-seeded (<25 g/100-seed weight) black, cream, and cream-striped beans are popular. The latter two predominate in the northeastern states, whereas black beans are more popular in the southern region (Vieira, 1988). Similarly, small black and/or red beans are consumed in Central America, Mexico, Cuba, and Venezuela, whereas, in the Andean countries of Colombia, Ecuador, and Peru, large-seeded red, pink, beige, and cream types, both solid and with various patterns of mottling, speckling, and spotting, are preferred. At least nine colors and sizes of beans are produced in sub-Saharan Africa. In Europe, North Africa, and western Asia, white, red, and cream-mottled beans of different sizes and shapes (but mostly medium and large) are consumed (Singh, 1992, 1999; Wortmann et al., 1998).

13.2.1 Climate and Soil Requirements

Although common beans are a warm-season crop, they are grown in a wide range of climates. In temperate areas they are grown in the warm season, and yields are usually higher in temperate than in tropical zones. Studies conducted at CIAT (1980) showed that approximately 80% of all bean production in Latin America is in regions where the mean temperature during the growing season is between 18°C and 25°C. Major production occurs in areas where the temperature is around 21°C (Laing et al., 1984). Bean seeds germinate poorly in soils colder than 15°C (Kooistra, 1971). Seedlings emerge after about 17 days when soil temperatures are 10°C–11°C, after 6–8 days at 13°C–14°C, and after only 5 days at 15°C–16°C (Scarisbrick et al., 1976). The optimum temperature

range for the germination of common bean is 20°C–30°C (Association of Official Seed Analysis, 1981; Scully and Waines, 1987). In general, high temperatures (>30°C) during flowering cause dropping of buds and flowers, which reduces the yield. High temperature during the night is more detrimental than during the day (Gross and Kigel, 1994). The bean plant is intolerant to frost and a short exposure to 0°C or below will kill bean tissue (Wallace, 1980).

Common bean is a small-farmer crop in Latin America and in eastern and southern Africa, where it is often cultivated in unfavorable conditions and with minimal inputs (Beebe et al., 2008). It is estimated that 60% of the bean crop is cultivated under the risk of either intermittent or terminal drought (Thung and Rao, 1999). Common bean (*Phaseolus vulgaris* L.) production in many regions occurs under rain-fed conditions where water deficit limits yield and causes instability of production (White et al., 1994). Highland Mexico, central America, Brazil, and much of eastern and southern Africa are bean producing areas where drought is common (Beebe et al., 2008). Although agronomic practices are important under water deficit conditions, cultivar improvement is usually seen as the most promising approach to increase yields. Recent studies indicate that direct selection for seed yield in common bean can be effective both for well-watered (Nienhuis and Singh, 1988; Singh et al., 1990) and deficit conditions (White et al., 1994). In the latter study, values for realized gain in seed yield of bulk F_3 populations (after selection among F_2 populations) ranged from 0.4% to 15.7% in four rain-fed environments. Nonetheless, yield testing is difficult and costly, and gains from selection are sometimes low. This situation has led to extensive research on mechanisms of adaptation to water deficit, not only in common bean but also in many other crops (Ludlow and Muchow, 1990). Such studies have sought to detect traits that either are more efficient as selection criteria than yield per se or aid in maximizing yield gains when selected simultaneously with yield (White et al., 1994).

Water requirements of common beans depend on soil and climatic factors, but the crop is considered to be poorly tolerant to water stress. Over 4 million hectares of common bean are grown annually in the drought endemic areas of northeastern Brazil and the central highlands of Mexico alone. Drought in these regions is unpredictable in duration, intensity, frequency, and stages of crop growth affected. Drought stress can be predicted more accurately in areas like Central America and coastal Peru where rains cease toward the end of the growing season, or where it seldom rains.

Drought tolerance in a broad sense, as defined by White and Singh (1991), encompasses all mechanisms that allow greater yields under soil moisture deficits. This includes a deep root system, early maturity, and other traits. Genotypic differences in response to moderate drought stress, measured as seed yield per hectare, have been found in Brazil, Mexico (Singh, 1992), and Colombia (CIAT, 1985; White and Singh, 1991). Consistent cultivar differences in drought response have been observed in repeated evaluations. However, long-term genetic studies and selection for drought tolerance have yet to be conducted in the tropics and subtropics. A single gene responsible for heat-drought tolerance was reported in snap bean (Bouwkamp and Summers, 1982), but its value in dry bean improvement is not known, especially in the tropics and subtropics. The little attention dedicated to breeding for drought tolerance has been due to lack of information on its inheritance, difficulties in using seed yield as a selection criterion in early segregating generations, the overriding effect of local adaptation, and lack of dependable and easily usable selection criteria. Thus far, work has been restricted to systematic evaluations of germplasm accessions and advanced breeding lines under field conditions (Singh, 1992).

Beans are more sensitive to water stress than deep-rooted crops like corn. Cowan (1977) cited a higher threshold leaf water potential for bean (about −0.8 MPa) than for corn (about −1.7 MPa). Water stress is especially deleterious at flowering and at the early pod determination phase (Stoker, 1974). Soils at field capacity are optimum for bean crops; plant growth is reduced at a soil water potential of −0.03 MPa and ceases at about −0.5 MPa (Wallace, 1980). The use of water-conserving systems for beans offers the possibility of increasing yields when water is limited. Use of crop residue as mulch, either alone or with tillage, has been reported to reduce soil water evaporation and erosion, increase in soil water storage, and increase in yields of various crops (Rajat De et al., 1983). Barros and Hanks (1993) evaluated the effects of mulch on bean evapotranspiration (ET), yield, and

water-use efficiency (WUE). Dry matter and seed yields were significantly greater for mulched than for bare plots. Mulched plots had a higher WUE (yield/ET) than did bare plots for a given irrigation level and yield increased as irrigation level increased. Seasonal differences in ET between bare and mulched plots were small. The yield–ET relation for mulch was linear and was distinctly different from bare soil, indicating a different partitioning of ET into soil water evaporation (Es) and transpiration (Tr). For the conditions of this experiment, mulch reduced Es by about 45 mm, at the same ET, and Tr was increased by 45 mm. However, for the same irrigation level, ET was lower for mulched than for bare plots, indicating that not all of the water saved went to transpiration (Tr).

Beans are also not suited to the very wet tropics, but they do well in areas of medium rainfall in tropical and temperate regions. Excessive rain causes flower drop and increases the incidence of diseases. Beans are also intolerant of poor soil aeration due to soil compaction and can tolerate a flooded soil for only about 12 h. Beans can grow on a wide range of soils, from sandy to clayey, provided water and drainage are adequate. The optimum soil pH for bean growth is reported to be in the range of 5.2–6.8 (Wallace, 1980), provided soil mineral nutrients are adequate. Fageria and Barbosa Filho (2008) studied influence of pH on shoot dry weight and seed yield grown on Brazilian Oxisol (Figure 13.1). Maximum yield of both these parameters was achieved at pH 6.4. Shoot dry weight was 30% greater at pH 6.4 than at pH 5.3. Similarly, seed yield was 32% greater at pH 6.4 compared to pH 5.3. Fageria (2001b) reported adequate soil pH of 6.2 for dry bean seed yield in a conventional planting system. Similarly, Fageria (2008) reported optimum soil pH was 6.5 for dry bean production in a Brazilian Oxisol in a no-tillage system. The increase in seed yield with increasing soil pH was associated with increased availability of nutrients, especially N, P, Ca, and Mg, and decreased Al^{3+} toxicity (Fageria and Baligar, 2003; Menzies, 2003). Other factors that might have contributed to increased yields with increasing pH are improved biological N_2 fixation and increased mineralization of soil organic matter and crop residues (Foy, 1984; Menzies, 2003). Yield components are also affected by increasing soil pH (Figure 13.2). As soil pH increased from 5.3 to 6.4, the number of pods per plant increased by 19%, the number of seeds per pod increased by 8%, and 100 seed weight increased by 3%. Fageria et al. (2008) also determined adequate soil acidity indices for dry bean grown on a Brazilian Oxisol in a no-tillage system (Table 13.1).

Bean is considered to be a salinity-susceptible crop, with a salinity threshold of about 1 dS m^{-1} (Maas and Hoffman, 1977).

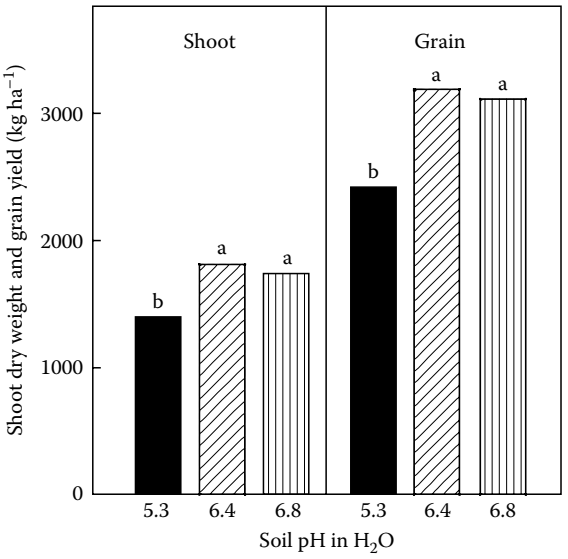

FIGURE 13.1 Influence of soil pH on shoot dry weight and seed yield of common bean. (From Fageria, N.K. and Barbosa Filho, M.P., *Commun. Soil Sci. Plant Anal.*, 39, 1016, 2008.)

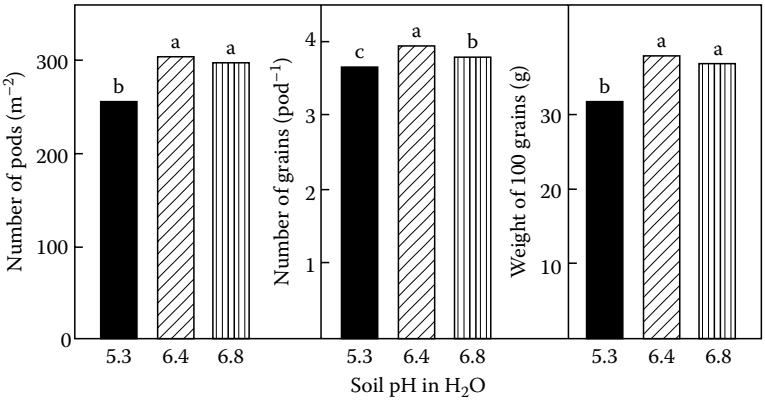

FIGURE 13.2 Influence of soil pH on yield components of common bean. (From Fageria, N.K. and Barbosa Filho, M.P., *Commun. Soil Sci. Plant Anal*., 39, 1016, 2008.)

TABLE 13.1
Relationship between Soil Acidity Indices and Seed Yield of Common Bean

Soil Acidity Indices	Regression Equation	R^2	AVMGY[a]
Ca ($cmol_c$ kg^{-1})	$Y = 800.9136 + 1068.0920X - 113.8684X^2$	0.7138**	4.7
Mg ($cmol_c$ kg^{-1})	$Y = 1556.4910 + 1807.4060X - 421.8893X^2$	0.7277**	2.1
H+Al ($cmol_c$ kg^{-1})	$Y = 3724.1220 - 193.0056X$	0.7056**	3.4
Acidity saturation (%)	$Y = 2984.1870 + 20.9478X - 0.4034X^2$	0.7503**	25.9
CEC ($cmol_c$ kg^{-1})	$Y = 5827.3090 - 338.8642X$	0.4121**	8.3
Base saturation (%)	$Y = 1266.4190 + 56.8195X - 0.4003X^2$	0.6652**	70.9
Ca saturation (%)	$Y = 1220.7300 + 81.9661X - 0.8106X^2$	0.6608**	50.6
Mg saturation (%)	$Y = 1721.3700 + 157.0069X - 3.8148X^2$	0.6885**	20.6
K saturation (%)	$Y = 9479.6660 - 7171.9450X + 1862.8360X^2$	0.3737**	2.2
Ca/Mg ratio	$Y = 4793.5800 - 573.3311X$	0.4610**	2.8
Ca/K ratio	$Y = 338.0114 + 264.9237X - 5.9895X^2$	0.6936**	22.1
Mg/K ratio	$Y = 1354.9580 + 460.6565X - 28.0475X^2$	0.6798**	8.2

Source: Adapted from Fageria, N.K. et al., *J. Plant Nutr*., 31, 1723, 2008.

AVMGY, adequate value for maximum seed yield

[a] Due to negative β_1 regression coefficient of some soil chemical properties, average value of the determined soil property at an optimum lime rate, which was considered optimum rate for statistically maximum yield, was considered for maximum yield.

** Significant at the 1% probability level.

13.2.2 Growth and Development

Mature seeds of common bean do not have a dormancy period; if climatic conditions (soil moisture and temperature) are favorable and the seed is of good quality, germination is complete in 4–5 days. Under normal environmental conditions, most of the *P. vulgaris* cultivars cultivated for dry seeds complete their life cycle in 70–95 days.

13.2.2.1 Seedling Morphology

Figure 13.3 shows morphological characters of a 1 week old bean seedling. It has two primary leaves, a trifoliate, gem, epicotyl, hypocotyl, and root system. The root system is composed of adventitious roots, basal roots, lateral roots, and taproot.

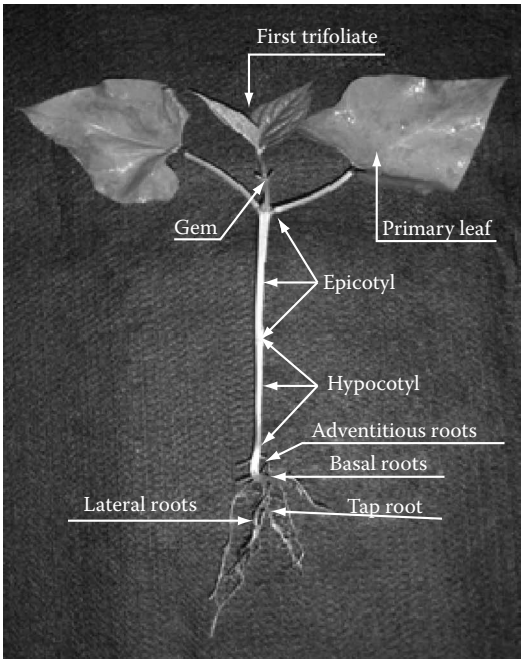

FIGURE 13.3 One-week-old seedling of common bean. (From Fageria, N.K. and Santos, A.B., *J. Plant Nutr.*, 31, 983, 2008.)

13.2.2.2 Roots

Understanding plant root growth is important for improving productivity of annual crops (Fageria et al., 2006). The root is an important plant organ because it not only absorbs water and nutrients but also provides mechanical support to the plant (McCully, 1999). In addition, roots can also synthesize growth substances and hormones such as cytokinins that may be important in leaf function and possibly seed development (Evans and Wardlaw, 1976). Decomposition of roots stimulates the activity of soil microbes and increases the soil organic matter content (Liang et al., 2002; Sainju et al., 2005). In addition, rhizodeposition, including root exudates, mucilages, and sloughed cells, may be a significant source of soil organic carbon (Sainju et al., 2005).

For plant growth analysis, the role of roots is generally ignored due to the difficulty in obtaining accurate root growth data under field condition. However, Wallace et al. (1972) reported that variation in root systems constitutes an important physiological genetic component of yield in annual crops. Root growth and morphology varies among plant species and cultivars within species, and they are sensitive to a number of environmental factors (Eghball et al., 1993; Baligar et al., 1998; Costa et al., 2002; Fageria et al., 2006).

Plants are often classified as fibrous-rooted or tap-rooted. Cereals are fibrous-rooted, and legumes are tap-rooted. Dry bean has taproot system with several lateral roots (Fageria and Santos, 2008). Species with a taproot generally can penetrate more deeply into the soil than species with fibrous roots. Vigorous root systems are desirable for better growth and development of a plant, especially under environmental stresses like drought and low soil fertility. Factors such as soil moisture content, soil fertility, soil aeration, and soil structure can greatly influence root development. Generally, the best root growth occurs when soil moisture is near field capacity, soil fertility is near optimum, and oxygen availability is sufficient for normal aerobic respiration. Soil structure is also critical, as poor soil structure, often caused by compaction, can restrict the supply of oxygen and increase the resistance of the soil to root penetration, significantly slowing root growth (Nelson and Larson, 1984).

Root and shoot growth are often tightly coupled. For example, when photosynthesis is active and plant shoots are growing rapidly, carbohydrates are translocated to the root system and it expands.

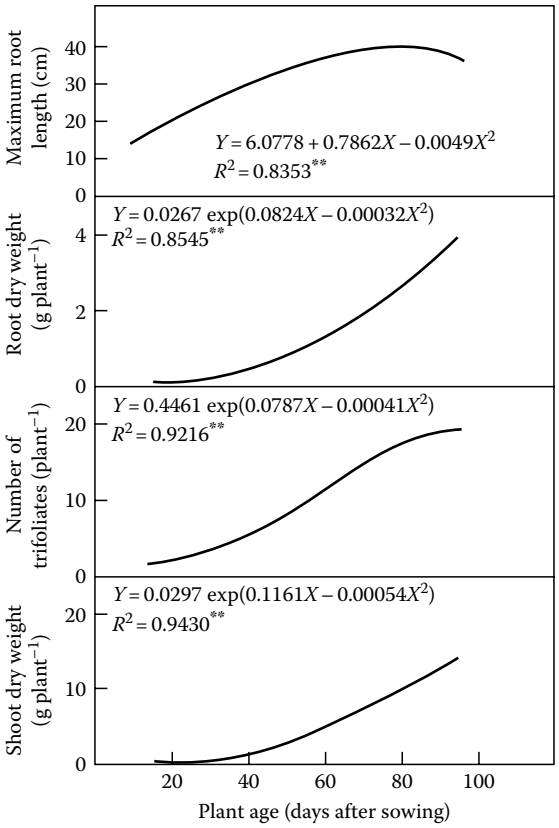

FIGURE 13.4 Relationship between plant age and dry bean growth parameters. (From Fageria, N.K. and Santos, A.B., *J. Plant Nutr.*, 31, 983, 2008.)

Alternatively, slow shoot growth may limit translocation of energy to the root system, limiting its growth. This mutual regulation of each other's growth is called the root–shoot interaction model (Osaki et al., 1997). Since the youngest growing portions of the roots are most active in water and mineral nutrient uptake, the root system must continually grow to provide adequate nutrition for the plant (Brown, 1984). Figure 13.4 shows maximum root length and root dry weight of dry bean during the growth cycle of the Brazilian cultivar BRS Valente under greenhouse conditions. Maximum root length was achieved at 80 days after sowing, and the increase in root dry weight was a reflection of shoot growth (Fageria, 2009).

Common beans, like many other legumes, have a taproot system with extensive lateral roots. The roots may grow to a depth of 1 m, but the lateral root system is mainly confined to the top 25 cm of the soil profile. The roots have nodules if inoculated with appropriate inoculants or if nitrogen-fixing *Rhizobium phaseoli* are present in the soil. Root growth is strongly influenced by environmental factors. White and colleagues have shown that drought tolerance in bean is related to depth of rooting (Sponchiado et al., 1989; White et al., 1990). Soil exploration by roots is associated with nutrient acquisition, especially in the case of immobile nutrients such as P. Genetic differences have been reported in common beans for root biomass, root-to-shoot ratio, and root biomass distribution (Stofella et al., 1979; Lynch and Beem, 1993; Fageria, 2009).

13.2.2.3 Shoot

Components of dry bean shoots include the main stem, branches, trifoliate leaves, flowers and pods. Figure 13.5 shows shoot dry weight as a function of plant age. Shoot dry weight increased with increasing plant age, and maximum dry weight was produced at 78 days after sowing.

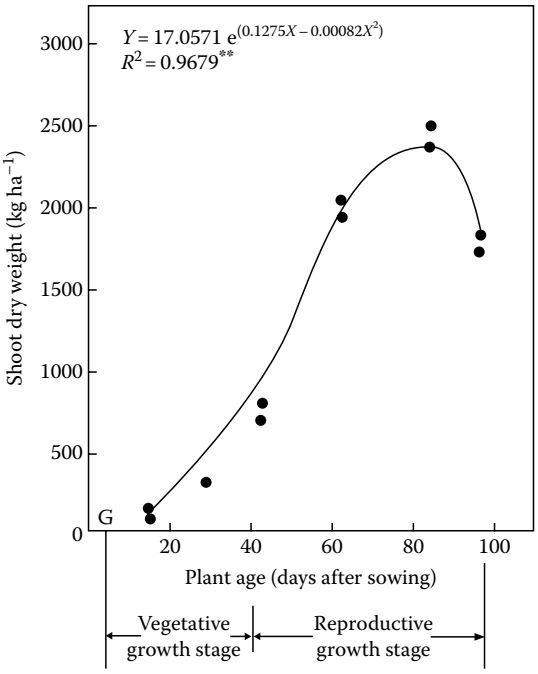

FIGURE 13.5 Relationship between plant age and shoot dry weight of dry beans grown on Brazilian Oxisol. (From Fageria, N.K. and Santos, A.B., *J. Plant Nutr.*, 31, 983, 2008.)

From 18 to 60 days shoot dry weight increase was almost linear. During this period, canopy development reached a maximum (Fageria and Santos, 2008). The decrease in shoot weight after 78 days of growth was associated with translocation of photoassimilates to pods. During this period some leaves senesced and fell, contributing to the decrease in shoot weight.

Shoot growth is an important determinant of seed yield. Figure 13.6 shows that seed yield increases with increasing non-seed shoot dry weight. The maximum seed yield of 3244 kg ha^{-1} was achieved with a non-seed shoot dry weight of 2098 kg ha^{-1}. Shoot dry weight explained 60% of the variation in seed yield (Figure 13.6). Peet et al. (1977) also reported a positive association between

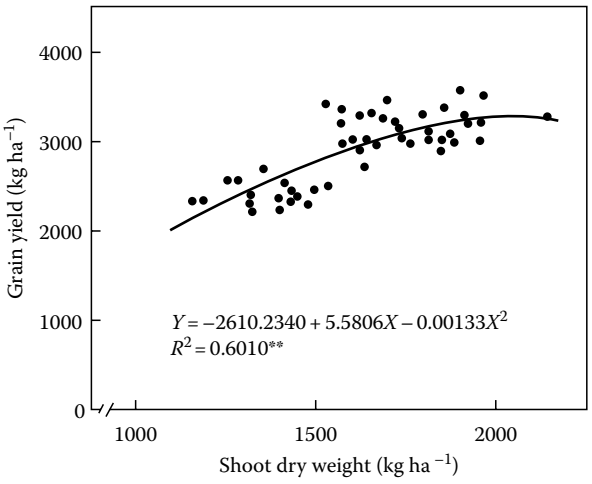

FIGURE 13.6 Relationship between shoot dry weights and seeds yield of dry bean. (From Fageria, N.K. and Santos, A.B., *J. Plant Nutr.*, 31, 983, 2008.)

TABLE 13.2
Cambridge and CIAT Systems of Growth Habit Classification in *Phaseolus vulgaris*

	CIAT Classification			
	I	**II**	**III**	**IV**
Growth Parameter	**Determinate Bush**	**Indeterminate Bush**	**Indeterminate Semiclimbing**	**Indeterminate Climbing**
Plant height (cm)	44	92	103	160
Nodes at flowering[a]	8	13	14	15
Nodes at maturity	9	17	19	23
Seed weight (mg/seed)	336	236	257	294
Days to flowering	34	39	38	40
Duration of flowering (days)	22	25	28	29

	Cambridge Classification					
	Indeterminate Climber (1)	**Indeterminate Semiclimber (2)**	**Indeterminate Bush (3)**	**Determinate Multinoded (4.I)**	**Determinate Intermediate Noded (4.II)**	**Determinate Bush (5)**
Number of nodes[a]	13–35	11–30	7–23	11–15	7–10	3–6
Branching (scale 1 to 9)	2–6	7–9	2–6			
Main stem length (cm)	70–300	30–150	20–70			

Sources: Compiled from Laing, D.R. et al., Field bean, in *Potential Productivity of Field Crops under Different Environments,* IRRI, Los Banos, Philippines, 227–248, 1983; Summerfield, R.J. and Roberts, E.H., *Phaseolus vulgaris,* in *Handbook of Flowering*, Haveley, A.H. (ed.), CRC Press, Boca Raton, FL, 139–148, 1984a.

[a] Nodes on main stem.

shoot dry weight and seed yield of dry bean. Wallace et al. (1972) reported that genetic improvement in economic yield of several crops derives in part from higher percentage of biological yield being partitioned to the plant organs constituting economic yield.

Common bean plants have long been classified as either bush or trailing (climbing), based on their growth habit. However, more complex classifications are needed to clearly differentiate the variation in been growth habits. One classification has been proposed by the International Center for Tropical Agriculture (CIAT), Colombia, and another by Cambridge University, England. These two classification schemes are summarized in Table 13.2. Singh (1982) simplified the CIAT classification and suggested a key for identification of four principal growth habits (Table 13.3). He gave a brief description of each of these growth habits and subtypes as follows:

Type I: Determinate growth habit; reproductive terminal buds on the main stem and branches; limited or no further node and leaf production after flowering commences. Branches and main stem generally strong and upright (Ia). Branches and main stem weak, prostrate, and possess some ability to climb (Ib).

TABLE 13.3
Key for Identification of the Principal Growth Habits of Dry Beans (*Phaseolus vulgaris* L.)[a]

a	b	c	d	e	f	g	
Growth Habit	**Terminal Bud**	**Growth**	**Stem and Branch Strength**	**Terminal Guide**	**Climbing Ability**	**Pod Load Distribution**	**Examples**
Type I	Reprod	D	Strong, upright	Absent or small	Absent or weak climber	Along the length	Sanilac, Canario 101, Calima, Pompadour Checa, Albia Cerrillos INTA
Type II	Veget	I	Strong, upright	Absent or small twining	Absent or weak climber	Along the length	Midnight, Porrillo, Sintetico, ICA Pijao Jamapa, Rio Tibago
Type III	Veget	I	Weak, open or prostrate	Small or medium twining	Weak or facultative climber	Concentrated in the basal portion	Pinto UI114, Flor de Mayo, Zamorano 2, Carioca, Cocacho
Type IV	Veget	I	Very weak, twining	Very large, twining	Strong climber	Along the length or concentrated in the upper portion	Garbancillo Zarco, San Martin, Cargamanto Bola Roja, Caballeros

Source: Adapted from Singh, S.P., *Annu. Rep. Bean Improv. Coop*., 25, 92, 1982.

[a]*Notes:* (1) For growth habit identification the first evaluation needs to be made during flowering and the final evaluation 3–4 weeks later. (2) The type of terminal bud separates growth habit I (reproductive) from other three intermediate types (vegetative). The strength of stem and branches separates type II (strong and upright) from other indeterminate growth habits (weak, prostrate, or twining). It is the combination of characters *e*, *f*, and *g* which separates type III from growth habit IV. For evaluation of the latter two types, varieties need to be grown with and without support. (3) Types I, II, and III do not require support, and their seed yield is much higher in monoculture than with intercropping.

D, determinate; I, indeterminate.

Type II: Indeterminate growth habit; vegetative terminal bud on main stem and branches; node and leaf production occur after flowering commences. Both main stem and branches strong and upright. The terminal guide or leader (excessively elongated and weak internodes) absent, thus lacking climbing ability (IIa). Terminal guide of varying length present and hence possesses some climbing ability (IIb).

Type III: Indeterminate growth habit. Branches relatively weak and open, semiprostrate, or twining. Pod load largely concentrated in the basal part of the plant. The maximum yield is realized in monoculture. Branches relatively short, guide on the main stem and/or branches is small when present and possesses weak climbing ability (IIIa). Branches long, often prostrate or twining, with relatively long main stem guide and moderate climbing ability (IIIb).

Type IV: Indeterminate growth habit. Stem and branches very weak and excessively long, possessing strong climbing ability. Support essential for maximum production. Pod load distributed all along the length of the plant (IVa). Pod load mostly borne on the upper part of the plant (IVb).

Common bean stems and branches are slender, twisted, angled, and ribbed; in climbing forms they have more nodes, which are further apart than in determinate bush types. Leaves are alternate, trifoliate, and somewhat hairy, and each has a well-developed pulvinus at the base (Summerfield and Roberts, 1984a). Common beans are normally self-pollinated and less than 1% natural crossing occurs.

13.2.3 Growth Stages

An understanding of bean growth stages is needed for better crop management practices and improved yields. Growth and development of common beans are divided into vegetative (V) and reproductive (R) stages. The V stages are defined on the basis of number of nodes on the main stem, including the primary leaf node, whereas R stages are defined on the basis of pod and seed characteristics in addition to nodes. The different V and R growth stages are presented in Table 13.4. The description of growth stages presented in Table 13.4 is based on the work of Lebaron (1974).

13.2.4 Dry Matter

Photosynthesis provides 90%–95% of plant dry weight (Kueneman et al., 1979). Thus, net photosynthesis of the entire plant canopy integrated over a growing season determines total plant dry weight and, indirectly, seed yield. *Phaseolus vulgaris* is a C_3 plant. Maximum values of net photosynthesis during the ontogeny of individual leaves range from 25 to 40 mg CO_2 dm^{-2} h^{-1} (Louwerse and Zweerde, 1977; Tanaka and Fujita, 1979). In southern Australia, Sale (1975) reported bean photosynthetic rates of 35–40 mg dm^{-2} h^{-1} at a saturation irradiance of 600–650 W m^{-2} and a leaf area index (LAI) of ~4.5. No change in net photosynthetic rate was recorded over a range of LAI values from 4.5 to 7.3. Silveira et al. (1996) determined the LAI of two Brazilian cultivars, Safira and Carioca, during the crop growth cycle, and maximum LAI occurred about 55 days after emergence. Dry matter production of roots and tops of three common bean cultivars grown in an Oxisol of central Brazil in a greenhouse experiment are presented in Table 13.5. In general, the dry weight of tops and roots increased with increasing age of the crop. This increase was greater in the tops than in roots. Maximum rates of dry matter accumulation in tops and roots of all the cultivars occurred from 30 to 60 days after sowing. The cultivars Carioca and CNF4856 produced more top dry matter than CNF10, possibly because their growth cycle was longer.

Fageria (1996a) measured dry matter yield of common bean throughout the growing season for several fertilizer P rates on Brazilian Inceptisol under field conditions. Dry matter yield increased with increasing P levels up to 348 kg P ha^{-1} applied broadcast, then decreased at greater rates (Figure 13.7). The decrease in dry matter at the highest P rate may be related to more photosynthate translocation to seeds and to the senesce of old leaves. Table 13.6 shows the correlation between seed yield and dry weight of pods of common bean and dry matter production at different growth periods. Dry matter production of roots, as well as tops, explained much of the variation in seed yield and pod dry weight at all growth stages except 17 days after sowing.

13.2.5 Yield Components and Yield

Number of pods per unit area, seed per pod, and weight of 100 seeds determine dry bean yield. To achieve maximum economic yield, all these yield components should be in balance. In addition, seed harvest index, N content of the plant, and N harvest index are important plant characteristics that are usually positively associated with seed yield (Denis and Adams, 1978; Sarafi, 1978; Nienhuis and Singh, 1986; Scully and Wallace, 1990; Fageria and Santos, 2008).

13.2.5.1 Number of Pods versus Seed Yield

The number of pods per plant and per unit area is among the most important yield components associated with seed yield of dry bean. Figure 13.8 shows relationship between number of pods per plant and seed yield of dry beans grown on a Brazilian Inceptisol. Dry bean yield increased significantly in a quadratic fashion with increasing number of pods per plant. The number of pods per plant explained 67% of the variation in seed yield. Bennet et al. (1977) reported that among yield components, pods per plant has often been recommended as an indirect selection criterion for increasing yield, primarily because of its higher and more consistent correlation with yield. Similarly, Wallace et al. (1972)

TABLE 13.4
Vegetative and Reproductive Growth Stages in Common Bean

Growth Stage	Description
Vegetative (V)	
V_1	Completely unfolded leaves at the primary (unifoliate) leaf node, average 1 day from sowing and having 1 node.
V_2	First node above primary leaf node, count when leaf edges no longer touch; average 19 days from sowing and having 2 nodes.
V_3	Three nodes on the main stem including the primary leaf node; secondary branching begins to show from branch of V_1 and average 27 days from sowing and having 3 nodes on main stem.
V_n	*n* nodes on the main stem, but with blossom clusters still not visibly opened. A new node each 3 days.
V_5	Bush (determinate) plants may begin to exhibit blossoms and become stage R_1. Average 50 days from sowing and 5 nodes on main stem.
V_8	Vine (indeterminate) plants may begin to exhibit blossoms and become stage R_1. Average 40 days from planting and 8 nodes on main stem.
Reproductive (R)—bush type	
R_1	One blossom opens at any node. Average 50 days from sowing and having 6 nodes.
R_2	Pods about 1.25 cm long at first blossom position. Average 53 days from sowing and usually 2–3 nodes.
R_3	Pods 2.5 cm long at first blossom position. Secondary branching at all nodes. Average 56 days after sowing and plant one-half bloom.
R_4	Pods about 8 cm long, seeds not discernible and average 59 days after sowing.
R_5	Seeds discernible, average 64 days after sowing.
R_6	Seeds at least 0.6 cm over long axis, average 66 days before sowing.
R_7	Oldest pods have developed seeds. Other parts of plant will have full-length pods with seeds almost as large as first pods. Pods will be developing over the whole plant. Average 72 days from sowing.
R_8	Leaves yellowing over half of the plant, very few small pods and these in axils of secondary branches, small pods may be drying. Point of maximum production has been reached. Average 90 days from sowing.
R_9	Mature, at least 80% of the pods showing yellow and mostly ripe. Only 40% of the leaves still green color. Average 105 days from sowing.
Reproductive (R)—vine type	
R_1	One blossom opens at any node. Tendril will begin to show. Average 40 days from sowing and 8 nodes on main stem.
R_2	Pods 1.25 cm long at first blossom position, 9 nodes on main stem and average 43 days from sowing.
R_3	Pods about 2.5 cm long at first blossom position. Half bloom. Ten nodes on main stem and average 46 days from sowing.
R_4	Pods about 5 cm long at first blossom position, 11 nodes on main stem and average 50 days from sowing.
R_5	Pods more than 7.5 cm long, seeds discernible by feel, 12 nodes on main stem and average 56 days from sowing.
R_6	Pods 10–12.5 cm long with spurs. Seeds at least 0.75 cm in long axis. Average 80 days from sowing.

TABLE 13.4 (continued)
Vegetative and Reproductive Growth Stages in Common Bean

Growth Stage	Description
R_7	Oldest pods have fully developed green seeds. Other parts of plant will have full-length pods with seeds near same size. Pods to the top and blossom on tendril. Average 70 days from sowing.
R_8	Leaves yellowing over half of plant. Very few small new pods per blossom developing, small pods may be drying. Point of maximum production has been reached. Average 82 days from sowing.
	Mature, at least 80% of the pods showing yellow and mostly ripe. Only 30% of leaves are still green and average 94 days from sowing.

Source: Compiled from Lebaron, M.J., A description: Developmental stages of the common bean plant, College of Agriculture, University of Idaho, Current Information Series, No. 228, 1974.

TABLE 13.5
Average Dry Matter Yields (g per Two Plants) of Tops and Roots of Three Bean Cultivars at Different Growth Stages under Greenhouse Conditions

	Carioca		CNF10		CNF4856	
Age (Days)	Tops	Roots	Tops	Roots	Tops	Roots
17	0.29	0.12	0.31	0.14	0.24	0.09
31	1.45	0.34	1.73	0.43	1.49	0.39
45	5.58	0.88	4.67	1.03	5.17	0.82
60	14.45	1.17	11.92	1.05	12.65	1.29
80[a]	18.33	1.29	14.38	1.36	19.24	1.48

Source: Fageria, N.K., *Trop. Agric*., 66, 249, 1989.
[a] Cultivar CNF10 was harvested at 68 days.

reported that the seed yield was highly correlated with the pod number in dry bean. Pods per plant are both genetically controlled and influenced by environmental factors. Liming of a Brazilian Oxisol significantly increased pod number, seeds per pod and weight of 100 seeds, and seed yield of dry bean, and the increases varied among genotypes (Fageria and Santos, 2008).

13.2.5.2 Seeds per Pod and Hundred Seed Weight versus Seed Yield

Number of seeds per pod and weight of hundred seeds are important yield components. These traits are strongly controlled genetically. However, both these traits are also influenced by environmental conditions (Tanaka and Fujita, 1979). Fageria and Santos (2008) measured seeds per pod for 20 common bean genotypes. Seeds per pod varied from 3.1 to 6.0, with an average value of 4.4. Tanaka and Fujita (1979) reported seed number per pod that varied from 3.0 to 5.4 in two bean cultivars and at different plant populations. Number of seeds per pod (X) were linearly related to seed yield (Y) ($Y = -4.6121 + 4.1534X$, $R^2 = 0.2116$) (Fageria and Santos, 2008).

Hundred-seed weight is also an important yield component in dry bean. It is often positively related to seed yield (Figure 13.9). Hundred seed weight is controlled genetically and also influenced by environmental factors (Tanaka and Fujita, 1979). Nitrogen fertility is an important factor affecting seed weight of dry bean. For example, Fageria and Santos (2008) reported that 100 seed weights of 20 dry

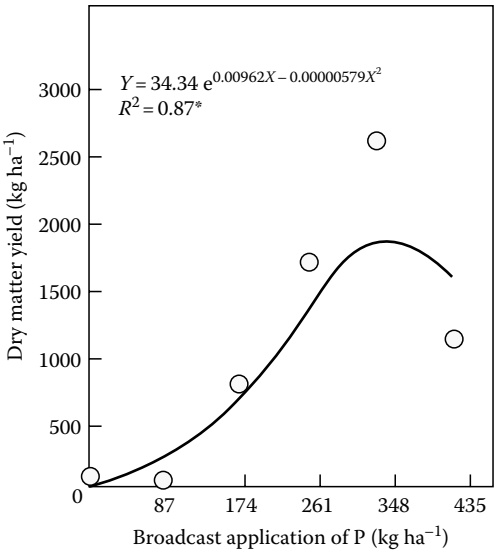

FIGURE 13.7 Dry matter yield of common bean as a function of P rates in an Inceptisol. (From Fageria, N.K., Evaluation of techniques for rice and common bean cultivation of lowland soils of central-west and north region, EMBRAPA-CNPAF, Goiania, Brazil, 1996b.)

TABLE 13.6
Correlation between Seed Yield, Pod Dry Weight, and Dry Matter Production in Common Bean

Variable		Seed Yield[a]	Pod Weight[a]
Root dry weight	17 DAS[b]	–0.12NS[c]	–0.15NS
	31 DAS	0.22*	0.23*
	45 DAS	0.48**	0.47**
	60 DAS	0.72**	0.74**
	Maturity[d]	0.68**	0.71**
Top dry weight	17 DAS	0.12NS	0.10NS
	31 DAS	0.51**	0.51**
	45 DAS	0.84**	0.85**
	60 DAS	0.83**	0.85**
	Maturity[d]	0.93**	0.96**

Source: Fageria, N.K., *Trop. Agric.*, 66, 249, 1989.

[a] Values are across three common bean cultivars: Carioca, CNF4856, and CNF10.

[b] DAS, days after sowing.

[c] NS, not significant; * and **, significant at 5% and 1% levels of probability, respectively.

[d] Cultivars Carioca and CNF4856 matured in 80 days; cultivar CNF10 matured in 68 days.

bean cultivars were significantly influenced by N rate, genotype, and genotype X N rate interaction. They varied from 6.5 to 20.4 g at the zero N rate (0 mg N kg^{-1}), with an average value of 11.8 g. At a higher N rate (400 mg N kg^{-1}), hundred-seed weights varied from 12.9 to 29.4 g, with average value of 17.9 g. Tanaka and Fujita (1979) reported that application of considerable amount of N is indispensable to obtain high yield of dry bean, because the N_2 fixation capacity of this crop is not significant.

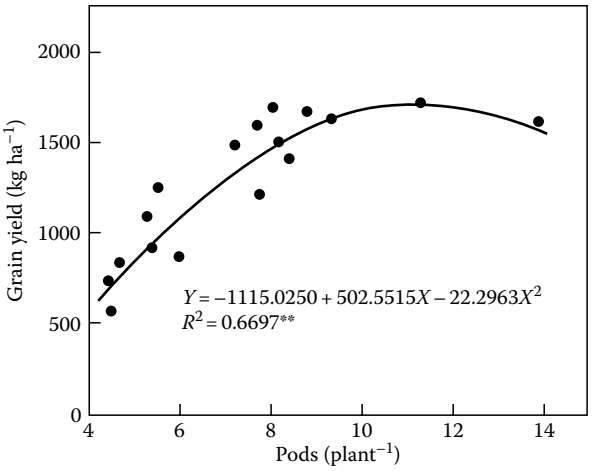

FIGURE 13.8 Relationship between number of pods and seed yield of dry bean grown on Brazilian lowland soil. (From Fageria, N.K. and Santos, A.B., *J. Plant Nutr.*, 31, 983, 2008.)

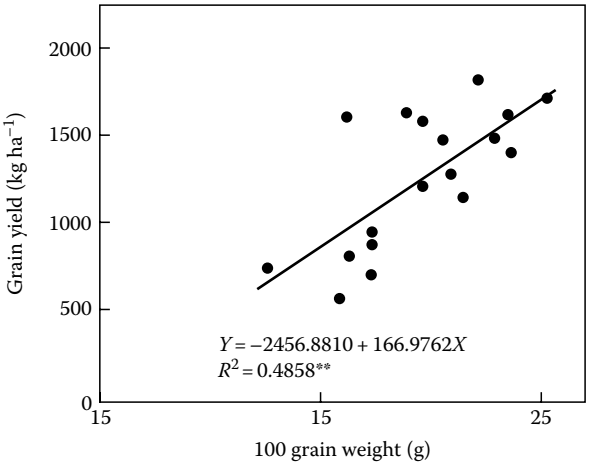

FIGURE 13.9 Relationship between 100-seed weight and seed yield of dry bean in Brazilian lowland soil. (From Fageria, N.K. and Santos, A.B., *J. Plant Nutr.*, 31, 983, 2008.)

13.2.5.3 Seed Harvest Index versus Seed Yield

Grain harvest index (GHI) is defined as the ratio between seed yield and seed plus straw yield. Part of the genetic improvement in yield of several crops is derived from a higher percentage of the biological yield being partitioned into plant parts comprising economic yield (Rasmusson and Gengenbach, 1984). According to Donald and Hamblin (1976), Beaven in 1914, was the first to consider the ratio of seed weight to total plant weight, and called this ratio the "migration coefficient." The migration coefficient concept was ignored for a long time. In 1962, Donald suggested the term grain harvest index and recommended it as an important reference to assess progress in germplasm development toward improved yield potential (Donald, 1962). The GHI did not become an important feature of crop assessment until after the publication of the review on GHI by Donald and Hamblin in 1976 (Hay, 1995).

The GHI has been improved significantly in the modern crop cultivars and consequently yields have risen. Sinclair (1998) reported that the GHI is an important trait associated with the dramatic increases in crop yields that have occurred in the twentieth century. Figure 13.10 shows the relationship between

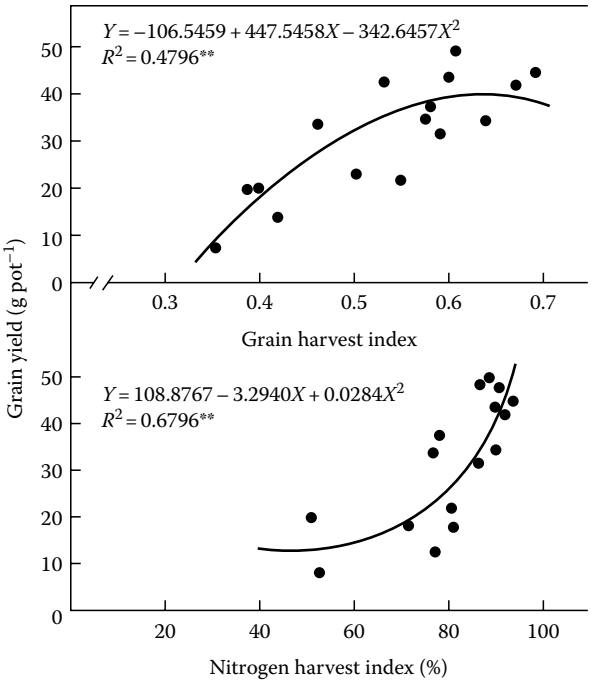

FIGURE 13.10 Relationship between nitrogen harvest index, seed harvest index, and seed yield of dry bean grown on Brazilian Lowland soil. (From Fageria, N.K. and Santos, A.B., *J. Plant Nutr.*, 31, 983, 2008.)

GHI and seed yield of dry bean under greenhouse conditions. Seed yield of dry bean increased significantly and in a quadratic fashion with increasing GHI. The variability in seed yield due to GHI was 48% and maximum seed yield was achieved at a GHI of 0.65. Peet et al. (1977) also reported a significant positive correlation with GHI and seed yield of dry bean cultivars.

Gifford and Evans (1981) reported that the improvement of yield potential in crops has come largely from an increase in the partitioning of assimilates into the harvested organs. These authors further reported that although this has been achieved by empirical selection by plant breeders, further increase may be more difficult, and an understanding of the factors that control partitioning could be helpful. Wallace et al. (1972) also reported that genetic improvement in economic yield of several crops has been due in part to a higher percentage of biological yield being partitioned to the plant organs constituting economic yield. Improved GHI represents increased physiological capacity (sink capacity) to mobilize photosynthate and to translocate it to organs having economic value (Wallace et al., 1972). Sinclair (1998) reported that at the beginning of the twentieth century, GHI of most seed crops was low, commonly about 0.3 or less, but it has increased dramatically with modern plant breeding.

Wallace et al. (1972) reported that dry bean cultivars differ greatly in GHI. Snyder and Carlson (1984) reported that harvest index of 23 cultivars of dry bean varied from 0.39 to 0.58. The GHI is also influenced by environmental factors (Wallace et al., 1972). Fageria and Santos (2008) reported that GHI of 20 dry bean genotypes varied from 0.21 to 0.54, with average value of 0.36 at a low N rate. At a higher N rate the GHI values varied from 0.42 to 0.59, with average value of 0.52. The increase in GHI produced by application of 400 mg N kg^{-1} of soil was 44% compared with 0 mg N kg^{-1} of soil. Hence, dry bean genotypes vary substantially in GHI, and N is an important nutrient in increasing seed harvest index of dry bean.

Snyder and Carlson (1984) reviewed literature on genetic control of GHI in several crops. These authors concluded that in the initial studies to increase the economic yield of a crop, when selection is based on a single parameter or on a ratio like GHI, it is important to monitor other yield

components that may influence economic yield. Snyder and Carlson (1984) also reported that the genetic gain was less when selecting solely on one parameter than when simultaneously selecting for two parameters.

13.2.5.4 Nitrogen Harvest Index and Seed Yield

The ratio of N accumulated in the seed to N accumulated in seed plus straw is called nitrogen harvest index (NHI). The NHI is positively associated with seed yield of dry bean, and NHI explained 68% or the variability in seed yield (Figure 13.10). Accumulation of large amounts of N is essential for high seed yields and, consequently, high GHI (Sinclair, 1998). Sinclair (1998) reported that N is a critical component of seed, and the partitioning of N to the seed could be crucial in influencing GHI. Evans and Seemann (1989) reported that in annual crops 50% of the N within the leaves can be directly involved in the composition and function of the photosynthetic apparatus.

The NHI varies among genotypes and is strongly influenced by N fertilizer application (Fageria and Santos, 2008). These authors reported that in a greenhouse treatment without N fertilizer (0 mg kg^{-1} soil), NHI varied from 0.43 to 0.82, with an average value of 0.63. At a high N fertilizer rate (400 mg kg^{-1}), NHI varied from 0.53 to 0.88, with an average value of 0.75. Genetic variability of NHI has also been reported in crop plants (Rattunde and Frey, 1986). High NHI is associated with efficient utilization of N (Welch and Yong, 1980). Selecting crop genotypes for high NHI may improve seed yields (Loffler and Busch, 1982).

13.2.6 Biological Nitrogen Fixation

The genus *Rhizobium* contains bacteria that are able to form morphologically distinct nodules on the roots of members of the Leguminosae. In the case of *P. vulgaris*, the *Rhizobium* species that preferentially invades the roots for nodule formation and nitrogen fixation is *R. phaseoli*. The overall reaction involved in the reduction of nitrogen to ammonia in *Rhizobium* can be summarized as follows, although the nature of the reductant is not firmly established (Rawsthorne et al., 1980):

$$N_2 + n\text{ATP} + 6\text{NADPH} + 2H^+ \rightarrow 2NH_4{}^+ n\text{ADP} + nP_i + 6\text{NADP}^+ + 6e^-$$

where n = 6.0–6.9 or 6.5 ATP/$NH_4{}^+$, depending on whether cell free or cell mass balance figures, respectively, are used (Bergersen, 1971).

Common beans are generally considered to be weak in N_2 fixation and show a variable response to inoculation (Vincent, 1974; Pereira and Bliss, 1987; Slatni et al., 2008). Acetylene reduction rates were estimated for 18 dry bean cultivars at Kimberly, Idaho (Westermann and Kolar, 1978). The calculated nitrogen fixation was about 10 kg N ha^{-1}, a small part of the total N uptake of 150–400 kg ha^{-1}.

Poor N_2 fixation by *P. vulgaris* has been attributed to the difficulty in establishing effective symbioses in the field and to plant genetic variability in the capacity to fix N (Graham, 1981). It is suggested by various researchers that N_2 fixation by common beans is usually unreliable, and N fertilization of field-grown plants is recommended (Graham, 1981; Westermann et al., 1981; Piha and Munns, 1987). Singh (1992) reviewed problems and prospects of nitrogen fixation in the tropics and subtropics. Bean cultivar and *Rhizobium* strain interactions, competition among efficient and inefficient bacterial strains, suppression of nodulation by residual soil nitrogen, high demand for phosphorus and photosynthate by *Rhizobium*, sensitivity to moisture stress, and interactions of these factors with environments have slowed the development of bean cultivars capable of high nitrogen fixation rates in the tropics and subtropics. Work carried out at CIAT (1981b) has suggested that there are prospects for increasing biological nitrogen fixation in *P. vulgaris* through breeding. A recessive gene mutation responsible for super-nodulation has been reported. In Canada, the mutant yielded significantly less than the parent cultivar, although its performance in tropical and subtropical soils remains to be determined (Singh, 1992).

Rhizobium tropici CIAT899 is a rhizobium wild-type strain that forms effective symbiosis with *P. vulgaris* (Martinez-Romero et al., 1991; Tejera et al., 2005). This strain has been shown to be tolerant to several abiotic stresses, including high temperature (Riccillo et al., 2000), low pH (Graham et al., 1994), and salinity (Khadri et al., 2001). Many reports have shown that tolerant strains are symbiotically more efficient than salt-sensitive ones under saline conditions (Chien et al., 1992; Tejera et al., 2005).

13.2.7 Nutrient Requirements

Application of adequate amounts of nutrients is a prerequisite for higher bean yields. In Latin America, where almost 50% of the world bean crop is produced, phosphorus deficiency is the main yield-limiting factor. At least 50% of the beans in Africa are grown on severely P-deficient soils (Yan et al., 1995). Nitrogen deficiency may also seriously limit yields in soils with low organic matter or in soils in which biological N_2 fixation is not effective due to high temperatures or soil restrictions. Potassium deficiency seldom occurs in Latin America, but beans are extremely susceptible to Al/Mn toxicity, which frequently occurs in many of its acidic soils. Among the minor-element problems, boron and zinc deficiencies are most commonly observed in soils of high pH or soils with a very low content of weatherable minerals (Schwartz et al., 1978).

Low P availability is a primary constraint to bean production in the tropics and subtropics (Fageria and Baligar, 2008). Fertilizers are not always available or affordable to farmers in the tropics and may be only marginally effective because of P fixation by Fe and Al oxides and allophane, making applied and native P unavailable to plants. Under these situations, the use of P-efficient bean cultivars may be a viable alternative or complement to fertilization. It is now well known that bean genotypes differ substantially in adaptation to low-P soils (Fageria, 2002).

Fertilizer recommendations for beans should be based on soil and plant tissue analyses. Fageria (1996b) determined a relationship between extractable P (by Mehlich-1 extracting solution) and relative yield for common beans grown on a Brazilian Inceptisol. When relative yield was 70%, the corresponding extractable P level was about 0–4.6 mg kg^{-1} (very low); when relative seed yield was 70%–90%, the extractable P level was 4.6–6.5 mg kg^{-1} (low); when relative yield was 90%–100%, the extractable P level was 6.5–8.5 mg kg^{-1} (medium); and when relative yield was more than 100%, the extractable P level was more than 8.5 mg kg^{-1} (high). These results are very useful in interpretation of soil analysis results for P fertilizer recommendations for bean crops in these Brazilian Inceptisols.

13.2.7.1 Nutrient Concentrations, Uptake, and Use Efficiency

A knowledge of nutrient concentrations (content per unit dry weight), nutrient uptake (concentration × dry weight) and nutrient use efficiency (yield per unit nutrient accumulated) is important for a basic understanding of plant nutrition. Fageria et al. (2007) determined concentration, uptake and use efficiency for common bean under field conditions (Tables 13.7 and 13.8). Concentrations of N, P, K, Zn, Cu, and Mn were higher in seed compared with shoot. Fageria (1989) reported similar trend in nutrient concentrations in shoot and seed of common bean plants under greenhouse conditions Piggott (1986) reported similar ranges of adequate concentration values for macro and micronutrients in common bean. Total nutrient uptake (shoot plus seed) in descending order was N > K > Ca > P > Mg > Fe > Zn > Mn > Cu. These uptake values can be taken as references for maintaining soil fertility for bean production in Oxisols.

Greater percentages of P and N were exported to the seed than other nutrients, followed by Cu, Zn, Mn, and K (Table 13.8). Transport of Fe and Ca was minimal. Fageria (2001a) reported a similar trend in transport of nutrients to seeds of bean grown on Oxisols. Nutrient use efficiency (seed yield per unit of nutrient accumulated) was maximal for Mg and minimal for N among macronutrients. However, among micronutrients, Cu use efficiency was highest and Fe use efficiency was the lowest. Demand for N was highest and Mg was lowest to produce 1 Mg seed in bean. Similarly, demand for Fe was highest and Cu was lowest among micronutrients to produce 1 Mg seed yield. Fageria (2001b) reported

TABLE 13.7
Nutrient Concentration and Uptake in the Shoot and Seed of Common Bean Crop at Harvest

	Concentration ($g\ kg^{-1}$ or $mg\ kg^{-1}$)[a]		Uptake ($kg\ ha^{-1}$ or $g\ ha^{-1}$)[a]	
Nutrient	**Shoot**	**Seed**	**Shoot**	**Seed**
N	6.3	32.0	16.9	124.1
P	0.6	3.8	1.6	14.6
K	15.5	16.8	41.2	63.8
Ca	7.3	2.2	22.0	8.5
Mg	3.0	1.6	8.9	6.2
Zn	23.8	32.0	61.7	123.3
Cu	3.6	9.0	9.2	34.6
Mn	11.8	12.6	31.1	48.7
Fe	349.4	71.1	1010.3	274.9

Source: Fageria, N.K. et al., *Commun. Soil Sci. Plant Anal*., 38, 1637, 2007.

Note: Values are averages of 2 years field experiments.

[a] Concentration values for macronutrients are in $g\ kg^{-1}$ and micronutrients in $mg\ kg^{-1}$. Similarly, values of uptake of macronutrients are in $kg\ ha^{-1}$ and micronutrients in $g\ ha^{-1}$.

TABLE 13.8
Nutrient Exported to Seed, Nutrient Use Efficiency, and Nutrient Requirement per Mg of Seed Production of Common Bean

Nutrient	Exported to Seed (% of Total Uptake)	Use Efficiency ($kg\ kg^{-1}$ or $kg\ g^{-1}$)[a]	Required per Mg Seed Yield (kg or g)[b]
N	88	27.4	36.5
P	90	238.2	4.2
K	61	36.7	27.2
Ca	28	126.5	7.9
Mg	41	255.5	3.9
Zn	67	20.9	48.0
Cu	79	88.1	11.4
Mn	61	48.4	20.7
Fe	21	3.0	333.1

Source: Fageria, N.K. et al., *Commun. Soil Sci. Plant Anal*., 38, 1637, 2007.

Note: Values are averages of 2 years field experiments.

[a] Nutrient use efficiency = (Seed yield in kg)/(Nutrient uptake in shoot plus seed in kg or g). Where macronutrient uptake in kg and micronutrient uptake in g. Macronutrients in $kg\ kg^{-1}$ and micronutrients in $kg\ g^{-1}$.

[b] Similarly, macronutrients in kg and micronutrients in g.

TABLE 13.9
Adequate Levels of Nutrients in the Common Bean Plant

Nutrient	Growth Stage	Plant Part	Adequate Concentration
			g kg^{-1}
N	Early flowering	UMB[a]	52–54
	Peak harvest	Pods	31
P	Early flowering	UMB	4–6
	Peak harvest	Pods	3
K	Early flowering	UMB	15–35
	Peak harvest	Pods	26
Ca	Early flowering	UMB	15–25
Mg	Early flowering	UMB	4–8
S	Early growth	WS	1.6–6.4
	Peak harvest	Pods	1.7
			mg kg^{-1}
Fe	Early flowering	UMB	100–300
	Peak harvest	Pods	70
Mn	Early flowering	UMB	50–400
	Peak harvest	Pods	27
Zn	Early flowering	UMB	35–100
	Peak harvest	Pods	34
Cu	Early flowering	UMB	5–15
	Peak harvest	Pods	5
B	Early flowering	UMB	10–50
	Peak harvest	Pods	28
M	56 DAS[b]	WS[c]	0.4

Source: Compiled from Piggott, T.J., Vegetable crops, in *Plant Analysis: An Interpretation Manual*, Reuter, D.J. and Robinson, J.B. (eds.), Inkata Press, Melbourne, Australia, 148–187, 1986.

[a] UMB, uppermost blade.

[b] DAS, days after sowing.

[c] WS, whole shoot.

similar amounts of nutrients required by common bean to produce 1 Mg of seed. To produce high bean yields in Oxisols, it is essential to maintain a high level of available soil N. Adequate tissue nutrient concentrations for common bean at harvest are presented in Table 13.9.

13.3 COWPEA

Cowpeas (*Vigna unguiculata* L. Walp.) are also commonly called black eye pea, black eye bean, southern pea, China pea, kaffir pea, and marble pea. Five subspecies of *V. unguiculata* are now recognized: *unguiculata*, *cylindrica*, *sesquipedatis*, *dekindtiana*, and *mensensis* (Verdcort, 1970).

West Africa and India are centers of diversity for cowpeas and they are cultivated as a seed, vegetable, and fodder legume in diverse agricultural systems in many countries of Asia, Africa, and Latin America (Ehlers and Hall, 1997; Garcia-Hernandez et al., 2005). Cowpea contains almost all the mineral and organic nutrients essential for animal and human nutrition, plus a number of unique organic phytochemicals that favor health (Garcia-Hernandez et al., 2005). The highest cowpea seed-producing nations are India, Brazil, Nigeria, and other West African countries (Summerfield et al.,

1983; Padi and Ehlers, 2008). Cowpeas are also produced in the Australia and southeastern United States and California (Sellschop, 1962; Dadson et al., 2005).

Cowpeas are an important source of protein for large numbers of people in developing countries. Chemically mature cowpea seeds contain an average of 23% protein, 60% starch, and 2% oil (Aykroyd and Doughty, 1964). The high-quality protein of cowpeas is also a natural supplement to that of staple cereal crops because of its high lysine content, but like other legumes, cowpeas are deficient in the sulfur amino acids, methionine, and cystine.

Besides human consumption of cowpea seeds, the whole plant is used as a livestock feed and for soil improvement. Cowpeas are usually used as hay or grazing crop where paucity of rainfall or lack of irrigation water does not permit the production of fine-stemmed and easily cured fodder such as alfalfa and clover. Cowpea hay and alfalfa hay are equally digestible, except that the fiber of cowpea hay is more digestible than that of alfalfa hay (Sellschop, 1962). Cowpea hay is poorer in digestible proteins and richer in total digestible nutrients than alfalfa hay (Van Wyk, 1955). The best stage for cowpea harvest for fodder is when the first pods turn yellow. At this stage, the leaves and pods still contain more than 60% of the total quantity of crude protein of the plant and there is less danger of loss of leaves in drying and handling the hay than when the crop is harvested later. In addition, Roberts et al. (2005) reported that root-knot nematodes-resistant cowpea is an effective cover crop for protecting susceptible vegetable crops grown under irrigation and its beneficial effects are enhanced by incorporation of its biomass into the soil.

13.3.1 Climate and Soil Requirements

Cowpea can be grown under a wide range of climatic conditions, but production is mostly concentrated in the tropics and subtropics. It is sensitive to cold and is killed by frost. The cowpea can tolerate heat and relatively dry conditions and can grow with less rainfall and under more adverse conditions than *P. vulgaris* (Purseglove, 1987; Ehlers and Hall, 1997). Mean temperatures greater than 28°C lead to abnormal pollen development and anther indehiscence, and low mean temperatures (around 20°C) reduce the yield of cowpeas (Warring and Hall, 1984). A study conducted by Bagnall and King (1987) over a temperature range of 21/16°C to 33/28°C (day/night) showed that maximum yields of cowpeas were obtained at 27/22°C (day/night) temperatures. These authors also concluded that seed yield was influenced by temperature after flowering in two ways: high temperatures decreased pod number, and mean temperatures below 21°C decreased seed number and size.

Adequate water is essential for high yields and the effects of water deficit on crop growth and yield depend on the degree of stress and the developmental stage at which the stress occurs. The most drought-sensitive growth stages are flowering and pod filling (Shouse et al., 1981; Fageria and Santos, 2008). According to Labanauskas et al. (1981), water stress during flowering and pod filling reduced seed yield by 44% and 29%, respectively, when compared to a control treatment. Water stress during the V stage had no significant effects on seed yield. Similar results were obtained by Turk et al. (1980) in their studies of cowpea yields. Cowpea is more drought tolerant than common bean. It is well known that dehydration of cowpea during drought is markedly delayed by morphological and physiological adaptations that reduce Tr or increase uptake of soil water. For example, under drought conditions cowpea can maintain high leaf and xylem water potentials by complete stomatal closure (Itani et al., 1992b). Further, cowpea can withstand drought due to the deep root system of the plant (Itani et al., 1992a). Plants in which dehydration is delayed can survive during a long period of time under drought conditions, and when water becomes available, recovery is rapid and yield reduction is minimized (Itani et al., 1993). Despite its inherent capacity to survive levels of drought that would render comparable crops unproductive (Ewansiha and Singh, 2006), significant differences exist among cowpea genotypes in drought tolerance (Mai-Kodomi et al., 1999; Hall, 2004; Padi, 2004; Dadson et al., 2005; Muchero et al., 2008).

Cowpeas are adapted to a wide range of soils, from sandy to clayey. The primary soil requirements are good drainage and the presence of or inoculation with the proper nitrogen-fixing bacteria

(Martin and Leonard, 1967). Cowpeas thrive on acid soils, and good yields were obtained around pH 6 on an Oxisol in central Brazil (Fageria, 1991). In a field trial on a Colombia Oxisol, at pH 4.2 and 78% Al saturation, yields were essentially doubled by an application of 0.5 Mg $CaCO_3$ ha^{-1}, which reduced Al saturation to 67% and gave a Ca saturation of 22% (Spain et al., 1975). Similarly, application of 0.5 Mg $CaCO_3$ ha^{-1} in Ultisols of Nigeria resulted in 85% of maximum growth for both Al-tolerant and Al-sensitive cowpea cultivars (Edwards et al., 1981). Cowpeas are considered to be moderately susceptible to soil salinity with an initial yield decline (threshold) at around 1.3 dS m^{-1}. Yields decrease about 14% per unit of salinity increase beyond this threshold (Maas and Hoffman, 1977).

13.3.2 Growth and Development

The cowpea is an annual herbaceous legume. No seed dormancy has been reported, and when environmental conditions are favorable and seeds are sown at the appropriate depth (3–4 cm), germination is complete in 3–4 days. Although, germination is epigeal, cowpea cotyledons do not persist. They can lose as much as 91% of their dry weight by emergence (Ndunguru and Summerfield, 1975). Such effective mobilization of cotyledonary reserves probably contributes to rapid hypocotyl elongation and might improve emergence in adverse edaphic conditions (Wien, 1973). Under favorable conditions, cowpeas develop strong taproot systems and have many spreading laterals in the surface soil. Growth habits of cowpea are erect, semierect, trailing, prostrate, and climbing; determinate types with terminal inflorescences are rare (Summerfield and Roberts, 1984b).

The first pair of leaves above the cotyledonary node is simple and opposite, but they exhibit considerable variation in size and shape (Faris, 1965). The trifoliate leaves arise alternately and the terminal leaflet is frequently long and of greater area than the asymmetrical lateral leaflets (Summerfield et al., 1974). The inflorescence of cowpea consists of a peduncle on which four to six units of flowers are formed alternately in acropetal succession. Each unit is a modified simple raceme consisting of 6–12 buds, and the entire inflorescence may be regarded as a panicle (Ojehomon, 1968). Cowpea may come into flower as early as 22–30 days after emergence, or not until after 90 days, and the crop may require a total duration of 210–240 days to mature (Summerfield and Roberts, 1984b). The cowpea is largely self-pollinated, but a small proportion of outcrosses usually occurs, especially in humid climates. As in other seed legumes, a considerable fraction of unopened buds and premature fruits are usually shed. Ojehomon (1968) has reported that 70%–88% of the buds are shed before anthesis and that flower abortion is one of the important factors responsible for low yields of cowpeas.

Numerous factors have been reported to be responsible for loss in productive potential of the crop. Among these are inadequate nucleic acid synthesis before and after anthesis, abnormal pollen formation, poor pollen germination, a large proportion of assimilates sequestered in older flowers and pods to the detriment of young ones, production of hormones (e.g., abscisic acid) by older pods that promote absorption of younger ones, warm and dry weather, and insect damage (Summerfield and Roberts, 1984b).

13.3.2.1 Dry Matter

Dry matter production of a crop is generally related to economic yield if all environmental factors are at optimum level during crop growth. Fageria (1991), reported a significant positive relation between seed yield and pod dry weight and dry matter of roots and tops of cowpea grown on an Oxisol in a greenhouse experiment. Root and shoot dry weights were significantly correlated with seed yield and pod dry weight throughout the growth cycle of the crop. Correlation coefficient values increased with age. This means that cowpea dry matter production at maturity can be a good indicator of seed yield. Correlation values for dry weight of tops were higher than for dry weight of roots.

The rate of dry matter production by cowpeas is closely related to the amount of solar radiation intercepted by the crop canopy (Wien and Summerfield, 1984; Fageria and Santos, 2008). In broad leaf crops, canopies are generally more planophile and require a lower leaf area for complete light

interception than in cereals (Monteith, 1969). In addition, crop growth rates, dry matter, and seed yields are generally lower for broad-leaf than cereal crops (Wien, 1982). If the available light could be distributed over a large leaf area by changing leaf angles, the productivity of broad-leaf crops with high leaf area indices might be increased (Duncan, 1971). Cowpea leaf area development was not limiting under field growing conditions when mean temperature varied between 23°C and 28°C. These conditions allow the canopy to attain a leaf area index of 3 by 35–40 days after emergence in stand densities of 7–16 plants m^{-2} (IITA, 1973; Littleton et al., 1979; Chaturvedi et al., 1980). The cowpea is a C_3 plant, and Littleton et al. (1979) measured maximum growth rates of 16–25 g m^{-1} day^{-1} by a determinate, erect cultivar growing at equidistant spacing. Kassam and Kowal (1973), reported that average crop growth rates might be expected to range between 18–25 and 25–29 g m^{-2} day^{-1} in the forest and savanna zones, respectively, in Nigeria, if the maximum rates of photosynthesis of individual cowpea leaves are taken to be 40–50 mg CO_2 dm^{-2} h^{-1}.

Cowpea harvest index values ranging from 0.57 to 0.64 have been reported by Summerfield (1977), and partitioning of dry matter to fruits was fairly constant for a cultivar grown under different climatic conditions (Summerfield et al., 1978).

13.3.3 Yield Components and Yield

As in other crops, cowpea seed yield is the product of the number of pods per unit area, number of seeds per pod, and weight per seed. These three yield components are affected by environmental factors and genotypes. Figure 13.11 shows how these three components increased in Oxisols of central Brazil with the application of phosphorus in a P-deficient soil. Among the three yield-controlling characteristics, 100-seed weight was affected the most and pod number the least by P fertilization.

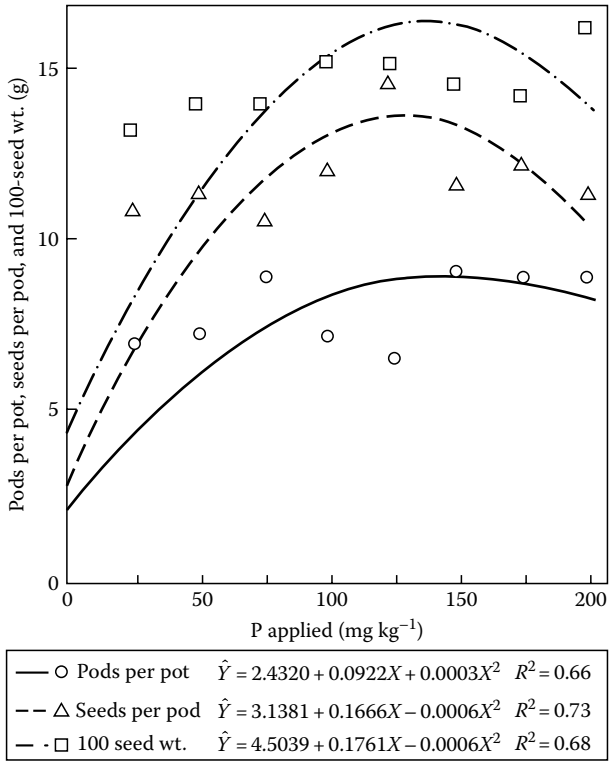

FIGURE 13.11 Influence of P on number of pods, seeds per pod, and 100-seed weight in cowpeas grown under greenhouse conditions in an Oxisol of Brazil.

Seed yields of cowpeas are quite low in all farming systems. Average world cowpea yields are about 380 kg ha^{-1} (Summerfield et al., 1983), but under good management and as a monoculture, cowpeas can produce yields of 1000–4000 kg ha^{-1} (Wien and Summerfield, 1984). This means that the low productivity of cowpeas is due to environmental factors and poor management practices rather than low yield potential.

13.3.4 Biological Nitrogen Fixation

Danso and Owiredu (1988) found that cowpea is readily nodulated by the indigenous rhizobia population present in Ghanaian soils. However, *Bradyrhizobium* isolates from soils across the different ecological zones of Ghana varied in their effectiveness, with a minority (26%) of the isolates effective in fixing nitrogen with cowpea, a majority (68%) moderately effective, and the remaining (6%) ineffective (Fening and Danso, 2002).

The quantity of nitrogen fixation by cowpea varies with environmental conditions and genotypes (Singh and Usha, 2003). According to Eaglesham et al. (1977), maximum rates of N assimilation occurred during pod-fill, and symbiotic fixation supplied over 80% of total plant N throughout growth and contributed significantly to seed N during late pod-fill, when nutrient N assimilation was negligible. The average value of N fixation by cowpea in properly conducted field experiments is about 198 kg N ha^{-1} per year (Nutman, 1976). Aguiar et al. (2001) reported that cowpea grown as a 70 days cover crop can fix 225 kg N ha^{-1} and add substantial amounts of organic matter to the soil.

13.3.5 Nutrient Requirements

Generally, farmers in Latin America, Asia, and Africa do not use fertilizers for cowpeas. But with fertilization, yields of this legume crop can be substantially increased if sufficient water is available during the growing season. Phosphorus is the most yield-limiting nutrient in acid soils in Latin America, Africa, and Asia, where cowpea is largely produced. Figure 13.12 shows that application of P fertilizer in combination with other nutrients can increase cowpea yields significantly. Smyth and Cravo (1990) determined the critical soil P levels in an Oxisol for cowpea (Figures 13.13 and 13.14). The critical Mehlich-1 P level was 8 mg kg^{-1}, and the Bray 1 critical P level was 13 mg kg^{-1}. Similarly Cox and Uribe (1992) determined that the critical extractable (modified Olsen) K level for cowpea grown on a humid tropical Ultisol was 0.10 cmol K kg^{-1} (Figure 13.15).

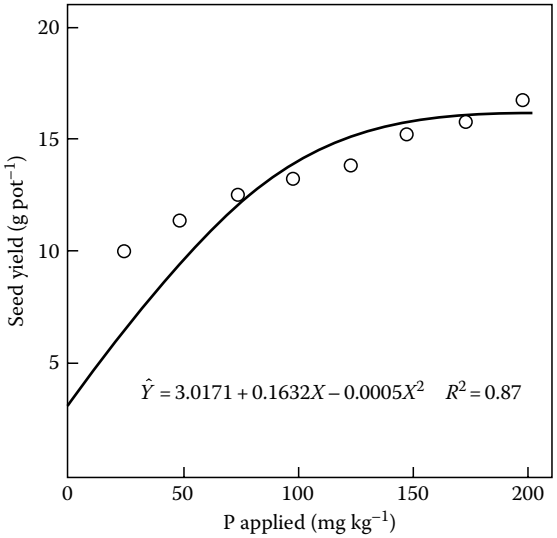

FIGURE 13.12 Influence of P fertilization on seed yields of cowpea.

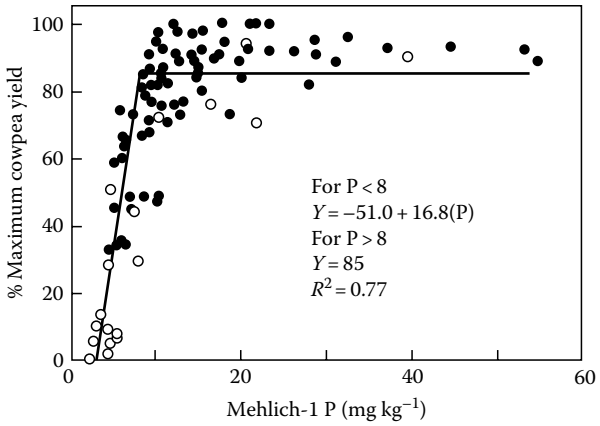

FIGURE 13.13 Relationship between cowpea yield and Mehlich-1 extracting soil P. (From Smyth, T.J. and Cravo, M.S., *Agron. J.*, 82, 309, 1990. With permission.)

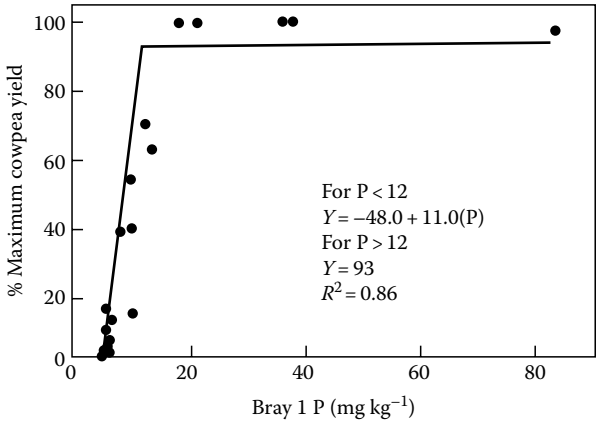

FIGURE 13.14 Relationship between cowpea yield and Bray 1 extracting soil P. (From Smyth, T.J. and Cravo, M.S., *Agron. J.*, 82, 309, 1990. With permission.)

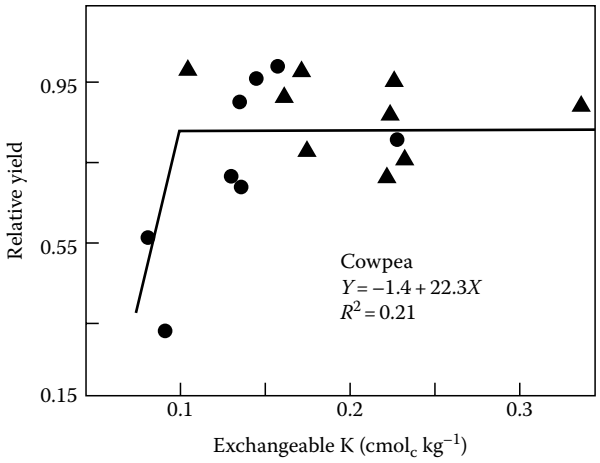

FIGURE 13.15 Relationship between cowpea yield and modified Olsen exchangeable K. (From Cox, F.R. and Uribe, E., *Agron. J.*, 84, 655, 1992. With permission.)

These results are useful in soil analysis interpretation results and making P and K fertilizer recommendations for cowpea crops.

Data on uptake of nutrients by cowpea crops under different agro-ecological conditions are scarce. According to Rachie and Roberts (1974), 1000 kg ha^{-1} seed yield of cowpea removed approximately 40 kg N ha^{-1}, 7.4 kg P ha^{-1}, 40 kg K ha^{-1}, 11.4 kg Ca ha^{-1}, 9 kg Mg ha^{-1}, and 4 kg S ha^{-1}.

The distribution of these nutrients in different plant parts as a percentage of the total plant is presented in Figure 13.16. On an average, 9% P was in roots, 53% in tops (excluding pods), 35% in seeds, and 3% in pod husks. The potassium distribution was 5% in roots, 49% in tops, 36% in seeds, and 10% in pod husks. The Ca distribution was 5% in roots, 82% in tops, 5% in seeds, and 8% in pod husks, and the Mg distribution was 9% in roots, 50% in tops, 21% in seeds, and 20% in pod husks. Zinc was distributed 19% in roots, 28% in tops, 46% in seeds, and 7% in pod husks. The iron

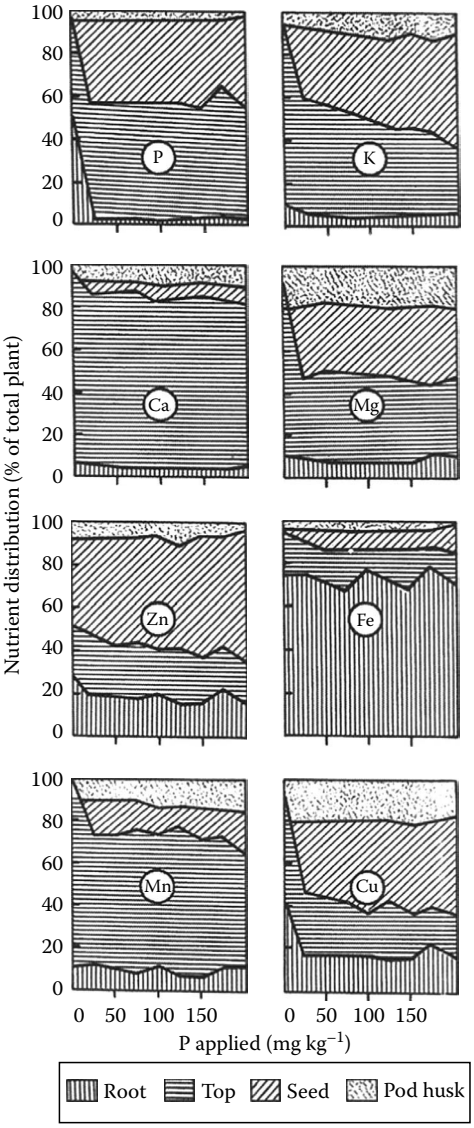

FIGURE 13.16 Distribution of nutrients in different parts of cowpeas grown in an Oxisol under greenhouse conditions.

TABLE 13.10
Adequate Nutrient Concentrations in the Cowpea Plant

Nutrient	Growth Stage[a]	Plant Part[b]	Adequate Concentration g kg^{-1}
N	39 DAS	Whole tops	28
	Early flowering	PUMB	11–17
P	56 DAS	Whole tops	3
	Early flowering	PUMB	1.2–4.0
K	42 DAS	PUMB	3.5–6.0
	62–90 DAS	All LB	2.7–6.0
Ca	39 DAS	Whole tops	9
	Early flowering	PUMB	7.2–10.0
Mg	Early flowering	PUMB	1.7–3.1
			mg kg^{-1}
Zn	42 DAS	LB	27–32
Mn	35 DAS	Whole tops	<1000
Fe	56 DAS	Whole tops	>100

Source: Compiled from Reuter, D.J., Temperature and sub-tropical crops, in *Plant Analysis: An Interpretation Manual*, Reuter, D.J. and Robinson, J.B. (eds.), Inkata Press, Melbourne, Australia, 38–99, 1986.

[a] DAS, days after sowing.

[b] PUMB, petiole of uppermost mature leaf blade; LB, leaf blade (excluding sheath or petiole).

content was highest in roots and lowest in pod husks; it was 72% in roots, 16% in tops, 9% in seeds, and 3% in pod husks. The manganese distribution was 10% in roots, 65% in tops, 14% in seeds, and 11% in pod husks. Similarly, 19% of the Cu was in roots, 28% in tops, 36% in seeds, and 17% in pod husks. These results suggest that cowpea roots retain maximum Fe and minimum K and Ca. Tops retain maximum Ca; almost 50% of the P, K, and Mg; and 65% Mn. Large amounts of P, K, Zn, and Cu are translocated to seeds. Pod husks contain a high amount of Mg and Cu. Adequate nutrient concentrations for the growth of cowpeas are given in Table 13.10.

13.4 SUMMARY

Common bean and cowpea are important warm-season seed legumes in temperate, tropical, and subtropical regions. Common bean was domesticated in Central America and/or northern South America. Cowpea probably originated in Africa. For both crops, many cultivars with different plant architectures and seed characteristics are available. Both crops can be grown on a wide range of well-drained soils and produce seed rich in protein but deficient in sulfur amino acids. Cowpea is more tolerant to acid soils, drought stress, and salinity than common bean. It also fixes a larger fraction of total nitrogen accumulated by the crop than common bean, and its total fixation of nitrogen compares favorably with that of soybean.

Flowering of both species is sensitive to both temperature and photoperiod, and considerable genotypic variation exists in plant response to both factors. In the tropics, common beans and cowpeas are grown both as monocultures and as intercrops or relay crops. In Latin America, most common bean production is found in areas with mean growing season temperatures of 18°C–25°C, but the climatic and cultural conditions of particular cultivars are highly specialized.

Farmers' yields of both crops are commonly low due to poor control of diseases, insects, water stress, mineral nutrition, and other adverse soil conditions. Substantial increases in farmers' yields

will require improving levels of inputs to minimize plant stress and developing cultivar tolerance to stress. Breeding for production-limiting factors helps recover yield potential of commercial cultivars, minimize production losses, reduce production costs, and stabilize yield. It also permits subsistence farmers to take advantage of improved cultivars, minimize the risk of spreading pathogen populations, reduce dependence on chemical pesticides and fertilizers, and increase WUE, thus maintaining a cleaner environment and conserving natural resources.

One metric ton of cowpea or common bean seed contains about 38 kg N, 5 kg P, and 15 kg K. To maintain soil fertility, nutrients (other than fixed nitrogen) should be returned through fertilizers or manure. Soil and tissue analyses can be used to diagnose and correct nutrient deficiencies and toxicities. Increased emphasis on breeding for nitrogen fixation may be needed in common bean.

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14 Peanut

14.1 INTRODUCTION

The peanut (*Arachis hypogaea* L.), commonly known as groundnut, earthnut, monkeynut, pinder, or goober, is both an oilseed crop and a food grain legume (Krapovickas, 1969). One of the world's most important oilseed crops, along with soybean, cottonseed, rapeseed, and sunflower, it is also a rich source of vegetable protein and is grown in 107 countries around the world (Wynne and Gregory, 1981; Upadhyaya et al., 2005). Approximately 53% of the total global production of peanut is crushed for high quality edible oil, 32% for confectionary consumption, and the remaining 15% is used for feed and seed production (Dwivedi et al., 2003). Peanut seeds contain 25%–30% protein, about 50% oil, 20% carbohydrate, and 5% fiber and ash. Properties of peanut oil are determined by the fatty acid composition. Approximately 90% of peanut oil is composed of palmitic acid (16 carbons and no double bonds: 16:0), oleic acid (18:1), and linoleic acid (18:2). Although many studies have identified genetic differences in the fatty acid composition in peanuts, most have examined a limited number of genotypes (Knauft and Wynne, 1995).

The cultivated peanut is found throughout the tropical and temperate regions of the world; however, wild species of *Arachis* are found only in South America, specifically in Brazil, Argentina, Bolivia, Paraguay, and Uruguay (Singh and Simpson, 1994). The genus *Arachis* contains a rich diversity of plant types. Both annuals and perennials are known, and although most species reproduce by seed, some are rhizomatous and reproduce largely through vegetative means. The species occur in ecozones, as different as the poorly drained, swampy areas near sea levels, in dry areas, and in mountainous regions at elevations up to 1600 m.

Arachis hypogaea L. originated in southern Bolivia or northern Argentina (Gregory et al., 1980). It is generally cultivated for human food and oil around the world. It is also used as a fodder for cattle in many Asian countries (Ramakrishna et al., 2006). The peanut was probably brought to Africa from Brazil by the Portuguese early in the sixteenth century and was later transported by the Spanish from the west coast of South America to Asia. The peanut may have reached the United States by way of slave ships from West Africa, although precisely when and where it was introduced is not known (Gibbons, 1980).

India, China, Indonesia, Myanmar, and Vietnam have the largest peanut-growing areas in Asia, while in Africa the major producers are Nigeria, Senegal, Sudan, the Democratic Republic of Congo, Chad, Mozambique, Zimbabwe, Burkina Faso, Uganda, and Mali. In the western hemisphere, the United States, Brazil, Argentina, and Mexico are the leading peanut producers. Peanut production in the United States occurs from the humid areas of Georgia and Florida to the arid areas of the Southern High Plains of Texas (Kiniry et al., 2005). In the United States, Valencia peanuts for the in-shell market are predominantly grown in eastern New Mexico and West Texas (Dwivedi et al., 2008).

Seventy percent of world peanut production occurs in the semiarid tropics, where drought, diseases, and insects are the main yield-limiting factors. Smartt (1994) reviewed global production practices and noted that they vary considerably. In the United States, Australia, and portions of South America, the crop is grown with intense management, generally with high levels of mechanical and chemical inputs. In parts of Africa and Southeast Asia the crop is grown together with other species, mainly to provide food and cooking oil for the farmer. In many countries, the crop is a monoculture, grown as a cash crop, primarily for export. The intensity of management varies considerably around the world, depending on the economic return for the crop or the role of peanuts

in farm subsistence. Altering plant population and row pattern can affect crop yield, quality factors, and pest development (Lanier et al. 2004). In the United States, peanut is generally grown in single rows spaced 91–102 cm apart; however, research suggests that pod yield can be increased by growing peanut in twin rows (18–23 cm spacing) on beds spaced 91–102 cm apart (Jordan et al., 2001; Lanier et al., 2004).

14.2 CLIMATE AND SOIL REQUIREMENTS

Although peanut is predominantly a crop of the tropics, the approximate limits of present commercial production are between latitudes 40°N and 40°S, where rainfall during the growing season exceeds 500 mm (Gibbons, 1980). Peanut performs well in dry climates with temperatures between 24°C and 33°C but can survive maximum daytime temperatures of up to 45°C if adequate moisture is maintained (Saxena et al., 1983). Soil temperatures lower than 18°C reduce germination and crop growth and temperatures higher than 37°C during pod development restrict pod and kernel growth resulting in lower pod yields (Vara Prasad et al., 2000; Ghosh et al., 2006).

Although the greatest recorded yield for the crop is 9.6 Mg ha^{-1} (Hildebrand, 1980), current commercial yields are 3.0–4.0 Mg ha^{-1} in many countries and as low as 1.0 Mg ha^{-1} in others (Upadhyaya et al., 2005). While the potential yield of peanut at any given location is unlikely to equal the record yield, it is likely that in most production regions current commercial crops fail to approach their potential. Climatic variability is a major cause of inability to achieve potential yield in irrigated and dryland production. Climatic variability can generate substantial production variability. Climatic variability can have severe consequences on individual farmers and on regionally based industries (Hammer et al., 1995).

In Asia and Africa, peanut is mostly grown as a rainfed crop. Dwivedi et al. (2003) reported that about 94% of the world peanut production is from rainfed crops grown largely by resource-poor farmers. Kassam et al. (1975) showed that, from sowing to harvest, a rainfed crop in Nigeria used 438 mm of water to produce a seed yield of 1.6 Mg ha^{-1} in 4 months. The crop water-use efficiency was 489 g water g^{-1} dry matter produced. Reddy (1977) gave a similar estimate of 444 mm water used by a high-yielding crop. Results from various studies showed that 500–600 mm of water, if reasonably well distributed, can produce satisfactory peanut yields (Gorbett and Rhoads, 1975; Stansell et al., 1976; Pallas et al., 1977).

Daily water use by peanut is low during the early growth stages and increases with an increasing leaf canopy. The maximum daily water use rate ranged from 0.5 to 0.6 cm day^{-1} (Stansell et al., 1976). The maximum water-use rates occurred 70, 80, and 95 days after planting for Tifspan, Florunner, and Florigiant cultivars, respectively (Stansell et al., 1976). The period of maximum evapotransiration (ET) for Spanish peanuts was reported to be 67–77 days after planting by Kassam et al. (1975), and from 55 to 80 days by Vivekanandan and Gunasena (1976). Kassam et al. (1975) observed that peak ET occurred shortly before the peak leaf area index (LAI) was achieved.

In Argentina, peanut production is concentrated mostly in the central region where unpredictable and intermittent periods of water deficit occur almost every year, especially during the pod growth period (Collino et al., 2001). In the United States, irrigation has become common. In the late 1970s, 45% of the allotted peanut acreage in Georgia was under irrigation, with new installations increasing steadily (Henning et al., 1979a,b). According to Boote et al. (1982), optimum water management appears to be scheduling irrigation to maintain less than 50% soil water deficit in the top 30 cm during early growth and irrigating at 25% soil water deficit during pod formation and seed growth. Some authors suggested that if the soil water potential is measured in the top 15–30 cm of soil, irrigation should be scheduled to maintain soil water potential above −0.6 bar (−60 kPa) on sandy or sandy loam soils, although irrigating to maintain soil water potential above −0.25 to −0.50 bar (−25 to −50 kPa) may be desirable during long, dry, hot periods occurring during the sensitive growth stages of pegging, pod formation, and early pod fill.

Peanut is mainly produced in the tropics and subtropics where it is widely grown on sandy and sandy loam soils (Murata et al., 2008). Murata et al. (2008) reported that in solution culture, the optimum pH for peanut development was around 6.0; however, Adams (1981) reported that peanut is one of the most acid-tolerant crops, with a critical pH range of 5–5.5. The most suitable soils for peanut production are well drained, light sandy loams with an ample supply of calcium and moderate organic matter (Gibbons, 1980; Saxena et al., 1983). Adams and Hartzog (1980) summarized the results from 78 field experiments in Alabama and found no correlation between soil pH and yield response of peanut to liming, but yield was highly correlated with exchangeable Ca. Peanut is considered moderately susceptible to soil salinity, and a salinity threshold (salinity at initial yield decline) of 3.2 dS m^{-1} has been reported (Maas and Hoffman, 1977). In practice, peanut is grown on a range of soils from alkaline to acid and from clays to fine sands (Gibbons, 1980). But peanut is highly susceptible to waterlogging, and harvesting can be a problem in clayey soils.

14.3 GROWTH AND DEVELOPMENT

Peanut is a self-pollinated, annual, herbaceous legume (family Fabaceae) that is erect or prostrate, sparsely hairy, and grows 15–60 cm high or higher. The species name *Arachis hypogaea* describes the most peculiar trait of the species; underground fruit formation (*hypo*, under; *agaea*, ground). The special feature of the peanut plant is that the fruit begins as a fertilized flower aboveground, but the pod and the seed mature under the soil surface. *Arachis hypogaea* consists of two subspecies, *hypogaea* and *fastigiata*, that differ in branching habit and seed dormancy. Each subspecies is further subdivided into two botanical varieties that correspond to market types. The two botanical varieties of the subspecies *hypogaea* are hypogaea and hirsuta. Hypogaea have alternate branching, a spreading or a bunching habit, and a long maturation period. Seeds undergo a period of dormancy after maturity and correspond to the Virginia market types. The botanical variety hirsuta is the Peruvian runner type. The subspecies *fastigiata* includes two botanical varieties, fastigiata and vulgaris. The botanical variety fastigiata corresponds to the Valencia market type and the botanical variety vulgaris to the Spanish market type (Gregory and Gregory, 1976).

Boote (1982) described the growth stages of peanut based on the visually observable vegetative (V) and reproductive (R) phases. The VE (emergence) stage is defined as the stage when the cotyledon is near the soil surface with some part of the seedling visible above the soil surface. The V0 stage is defined as when the cotyledons are flat and open at or below the soil surface. The V1 growth stage occurs when the leaflets of the first tetrafoliate leaf are unfolded and are flat in appearance. Stages V2 to Vn refer to the vegetative growth stages when the plant has 2 to *n* expanded leaves. According to Boote (1982), the R stages are R1 (beginning bloom), R2 (beginning peg), R3 (beginning pod), R4 (full pod), R5 (beginning seed), R6 (full seed), R7 (beginning maturity), R8 (harvest maturity), and R9 (overmatured pod). Knowledge of growth stages is important to better schedule a variety of cultural practices, including irrigation; control of weeds, diseases and insects; and harvest.

14.3.1 Germination and Seedling Growth

The first visible evidence of germination is the emergence of the radicle. Radicle emergence occurs by 24 h or earlier for the vigorous Spanish-type seed, but requires 36–48 h in the Virginia types. The hypocotyl carries the cotyledons to the soil surface, and the length of the hypocotyl is dependent on the depth of planting. Research at ICRISAT (1987) showed that 5 cm is the best sowing depth for peanut, since deep sowing (10 cm) reduced pod yields by 30% due to lower crop growth rates after emergence. During the first few days, the developing seedling depends on food reserves in the cotyledons for energy. After 5–10 days, depending on the type of peanut and the environmental conditions, the seedling becomes autotrophic (Ketring et al., 1982). The optimum temperature for peanut germination is about 30°C–35°C.

14.3.2 Roots

The peanut plant has a relatively deep taproot system with well-developed lateral roots. Nodulation is governed by proper inoculation, as well as type of soil, genotype, and climatic factors. Rooting depth controls water extraction from the soil profile. The maximum depth of peanut roots varies with soil and cultivar but ranges from more than 2.5 m in Florida sands (Boote et al., 1982) to only 1.2 m in an Alfisol in India (Gregory and Reddy, 1982). Hammond et al. (1978) reported that peanut roots can grow to a depth of about 200 cm in a well-drained sandy soil. Root densities in this soil were 1.5 cm cm^{-3} in the 0–30 cm zone and 0.1–0.4 cm cm^{-3} at greater depths. Robertson et al. (1979) reported that peanut roots were uniformly distributed under the row and laterally 46 cm from the row. The maximum root density was within the top 30 cm depth, which was above a tillage pan. Roots, which did penetrate the pan, extended to depths greater than 150 cm.

McCloud (1974) reported that the peanut root weight in the top 15 cm of soil was 37% of the total crop dry matter at 21 days after planting (DAP), but only 1.5% at harvest. Root dry weight in the top 15 cm of soil reached a maximum by 78 days after planting. Ketring et al. (1982) minimized the importance of extracting the complete peanut root system for calculations of the total plant dry matter comparison because the root dry weight is usually a small percentage of the total plant biomass.

Even though the fibrous peanut roots below the usual harvesting depth of 30 cm constitute a small fraction of the root weight, they are important in the water uptake and the drought tolerance of the crop. The water in the top horizon is freely available and is utilized rapidly at a rate determined largely by the leaf area index and evapotranspiration. However, the water below this surface horizon is utilized much more slowly (at 50% or less of potential evapotranspiration) (Boote et al., 1982; Meisner and Karnok, 1992).

14.3.3 Tops

Most peanut varieties have a bunch growth habit. The lateral branches rarely exceed the length of the main stem in the Valencia varieties, but they usually do so in the Virginia bunch varieties (Gibbons et al., 1972). Peanut leaves are alternately arranged in a spiral (2/5 phyllotaxy). They are pinnate, with petioles 3–7 cm long and two opposite pairs of leaflets about 1–7 cm long. Individual flowers emerge in sequence on the inflorescences. After fertilization, an intercalary meristem at the base of the ovary generates a stalk-like structure, the peg, which soon becomes positively geotropic and may extend to as much as 20 cm as it forces the fertilized flower under the soil surface (Bunting and Elston, 1980). The ovary matures underground into a pod with one to four seeds. The plant has an indeterminate growth habit. Flowers first appear about 30 or 40 days after sowing, and the plant may continue to produce flowers throughout much of its remaining growth (Ashley, 1984).

14.3.4 Dry Matter

The dry matter accumulation pattern in peanuts is similar to that of most other annual field crops. It is slow in the beginning, increases sharply in the late vegetative and early pod-filling stages, and reaches a plateau during late pod filling. Early top growth is composed mostly of main stem elongation and leaf production, but lateral branches account for the bulk of later growth (Ketring et al., 1982). Most of the dry matter is in the leaf blades and stems in the early stages and in the pods and stems at the later stages (Enyi, 1977).

The maximum crop growth rates of 13–24 g m^{-2} day^{-1} have been reported under different environmental conditions and for different cultivars (Williams et al., 1975; Enyi, 1977; Duncan et al., 1978). Duncan et al. (1978) reported that the selection for higher yield in peanuts has not resulted in a corresponding increase in crop growth rate. A large part of yield differences among peanut cultivars with nearly identical growth rates is due to differences in the partitioning of the dry matter to the fruits.

The crop growth rate of legumes is generally less than that of cereals because both the leaf area and the rate of dry weight increase per unit of leaf area are smaller in legumes than in cereals (Bunting and Elston, 1980). This may be associated with an indeterminate fruiting habit, which compels the crop from an early stage of development to divide its assimilate between making leaves and filling fruit (Bunting and Elston, 1980). Another reason is that legumes devote a substantial amount of assimilate to respiration associated with dinitrogen fixation.

Bell et al. (1993) found that variation in dry matter production is due to the effects of a differing leaf area duration on cumulative intercepted photosynthetically active radiation. Their work also found genetic differences in sensitivity to night temperatures, with cultivars adapted to cool environments potentially producing higher yields.

14.3.5 Leaf Area Index

Leaf area is one of the principal crop parameters affecting photosynthesis. LAI varies with environmental conditions, cultural practices, and the stage of crop growth. For determinate crops, the best time to measure LAI is when it reaches its maximum at the beginning of reproductive growth; for indeterminate crops the maximum LAI may occur well after flowering begins. The maximum peanut LAI values ranging from 3.3 to more than 7.0 have been reported in the literature (Williams et al., 1975; Saxena et al., 1983; Kiniry et al., 2005). The LAI reaches a maximum value 65–75 days after sowing in cultivars with a 115- to a 125 day growth cycle (Kassam et al., 1975; Williams et al., 1975; Enyi, 1977; Saxena et al., 1983). Misa et al. (1994) reported that the optimum LAI among 11 peanut genotypes ranged from 3.2 to 4.0. Duncan et al. (1978) reported that LAI continued to increase to more than 7.0 in some cultivars, but light interception reaches a maximum at an LAI of about 3.0. Further increases in LAI were assumed to have little effect on the crop growth rate.

The photosynthetic unit of the peanut plant is the compound leaf with two opposite pairs of leaflets. The maximum apparent photosynthetic rates for peanut leaves range from 0.6 to 1.8 mg CO_2 m^{-2} s^{-1} (Henning et al., 1979b) with a mean value of 1.06 mg CO_2 m^{-2} s^{-1} (Pallas, 1973; Ketring et al., 1982). Pallas and Samish (1974) evaluated the photosynthesis of peanut leaves at irradiances from 180 to 1546 μmol m^{-2} s^{-1}. Leaf photosynthesis was not light-saturated in that range. This wide variability is mainly due to genotypic differences, differences in leaf age and position, and variation in environmental conditions. For example, young leaves have greater net photosynthesis rates than older leaves, and when exposed to high irradiance, the lower leaves in the canopy have a lower photosynthetic potential than the higher leaves in the canopy (Henning et al., 1979a). In addition, a photosynthetic response to different levels of irradiance is strongly influenced by the irradiance under which the plants were previously grown. Plants previously grown under high irradiance are better able to respond to subsequent high light levels than plants previously grown under low irradiance (Bourgeois and Boote, 1992).

14.3.6 Grain Harvest Index

The grain harvest index (HI) (ratio of the weight of seeds to total dry matter above ground at harvest) of peanut varies between 0.33 and 0.58 (Bunting and Elston, 1980; Kiniry et al., 2005). Kiniry et al. (2005) reported that though the mean peanut HI was 0.45, it varied greatly among cultivars, locations, seasons, and ecosystems. However, if allowance is made for the high energy value of the oil component of the seeds compared with the rest of the plant, the peanut HI of 0.45 is equivalent to a cereal HI of almost 0.6 (Ashley, 1984).

Among peanut varieties, more determinant types in which the plant vegetative structure is smaller and formed over a shorter time, tend to have a larger HI than the longer-lived and more freely branched indeterminant types, in which vegetative growth is not arrested by flowering (Bunting and Elston, 1980). The shelling percentage is about 80% for the early-maturing determinant types compared with 60%–75% for the spreading indeterminant cultivars (Saxena et al., 1983).

14.4 YIELD COMPONENTS

A better understanding of yield components and their association with yield can be used in breeding for yield improvement (Slafer, 2003; Phakamas et al., 2008). In addition, a selection for specific physiological traits could complement conventional breeding approaches and hasten yield improvement (Boote et al., 2001; Araus et al., 2002). In peanut, seed yield per unit land area is the product of pod number per unit area, number of seeds per pod, and weight of individual seeds. Seeds per pod vary from 2 to 6, pods per plant vary from 50 to 104, and 100-seed weight varies from 28 to 62 g (Enyi, 1977; ICRISAT, 1987). This variation is related to the cultivar, plant spacing, fertilizer, and climatic conditions. All three yield components are most sensitive to environmental stress during the flowering and the kernel-filling growth stages.

14.5 NUTRIENT REQUIREMENTS

An adequate supply of essential nutrients is necessary to obtain high yields of peanuts. A balanced fertility program with particular emphasis on adequate levels of P, K, Ca, and Mg is essential to high yields (Henning et al., 1982). Peanuts, like other legumes, can fix nitrogen, with nitrogen fixation often contributing to over 50% of the total N in the plant at maturity (Pimratch et al., 2004).

However, small amounts of N should be applied as starter fertilizer to stimulate growth before nodulation and nitrogen fixation begins. The peanut can fix atmospheric N if the correct strains of nitrogen-fixing bacteria (*Bradyrhizobium*) are present in the soil. The peanut is also nodulated by a large group of *Rhizobium* strains classified as the cowpea miscellany (Buchanan and Gibbons, 1974). Inoculation of peanuts grown in rhizobia-free soil resulted in significant yield increases (Reddy and Tanner, 1980; Kremer and Peterson, 1983).

Soils often contain rhizobia that are highly competitive against those applied in inoculants. Selected strains of peanut *Rhizobium* failed to increase yields in the presence of high populations of indigenous rhizobia (Diatloff and Langford, 1975). However, Nambiar et al. (1984) reported that inoculation with *Rhizobium* increased peanut yields in fields where the crop had been previously grown at ICRISAT, India.

Adverse environmental conditions cause the inoculant quality to deteriorate. Hot and dry conditions at planting can cause a rapid decrease in rhizobia applied to seeds (Hardaker and Hardwick, 1978). Successful inoculation requires carriers capable of delivering high numbers of effective rhizobia under adverse conditions to ensure the nodulation of the host legume (Kremer and Peterson, 1983). In addition, rhizobia differ in their ability to fix N_2, and the presence of nodules on roots of the peanut plant does not necessarily mean that sufficient N_2 is being fixed for the maximum growth of the host plant (Nambiar, 1985). Hence, it may be necessary to introduce superior strains of *Rhizobium* and apply some nitrogen to ensure an adequate nitrogen supply for maximum growth and yield of the host plant. However, Lanier et al. (2005) reported that peanut pod yield increased with increasing rates of N fertilizer even though the crop was inoculated with nitrogen-fixing bacteria. This suggests that, at very high yield levels, the N requirements of the nodulated peanut cannot be met from symbiotic N_2 fixation alone (Nambiar et al., 1986). Bronson et al. (2004) reported that producers typically use rates of N fertilizer up to 120 kg ha^{-1} in the southern High Plains of Texas.

One of the most common peanut production problems occurs in soils with low calcium concentrations. When peanuts are grown in these soils without additional calcium, pod rot, and poorly filled pods are common (Gascho and Davis, 1994). Genetic differences exist in response to effects of varying soil calcium concentrations, with large-seeded types generally requiring approximately twice the soil calcium concentration as small-seeded types (Walker and Keisling, 1978; Gascho and Davis, 1994). Several studies examining genetic differences in seed and pod calcium levels have identified the ratio of the pod surface area to seed weight as the cause of the greater calcium requirements in large-seeded types, rather than a genetic difference in the amount of calcium required per unit weight of seed (Gascho, 1992). Adams et al. (1993) also identified genetic differences in

requirements for ambient soil solution calcium concentrations; however, the low cost of calcium supplements to the soil have made breeding for this trait a low priority.

Iron deficiency is observed in peanut plants grown on calcareous soils (Zuo et al., 2003; Zuo and Zhang, 2008), and using iron efficient genotypes is the best strategy to correct this problem. Gao and Shi (2007) reported significant differences in Fe use efficiency in peanut genotypes grown on calcareous soil. These authors also reported that for Fe-efficient peanut cultivars, an Fe reduction capacity and the release of hydrogen ions from the roots increased under the Fe deficiency stress. High correlations ($R^2 = 0.79$) were observed between the sum of the root Fe reduction and the field chlorosis scores for 16 cultivars.

Jolley et al. (1996) reported that in many species, iron deficiency induces some physiological and biochemical responses that increase the iron availability in the rhizosphere. Dicotyledonous plants respond to iron deficiency by enhancing the activity of Fe^{3+} chelate reduction at the root surface, by the acidification of the external medium by H^+ extrusion, and by the release of chelating substances like citrate by the roots (Krouma et al. 2003). Marschner et al. (1986) reported that the peanut responds to Fe-deficiency stress by releasing hydrogen ions and other reductants from the roots and by increasing the reduction of Fe(III) at the plasmalemma.

14.5.1 Nutrient Concentration and Uptake

The importance of plant tissue analysis to diagnose the nutrient status of crops during the growing season is widely recognized (Dow and Roberts, 1982). Sahrawat et al. (1987) studied the concentration changes in peanut leaves with time. Concentrations of N, P, K, Cu, Mn, and Zn in the leaves of the cultivar RMV2 generally decreased with increasing age. The concentrations of Ca increased markedly with leaf age, and Mg concentrations tended to increase. Adequate concentrations of macro- and micronutrients in peanut plants are presented in Table 14.1.

TABLE 14.1
Adequate Concentrations of Nutrients in the Upper Stems and the Leaves of the Peanut Plant at Early Pegging

Nutrient	Concentration (g kg^{-1} or mg kg^{-1})[a]
N	35.0–45.0
P	2.0–3.5
K	17.0–30.0
Ca	12.5–17.5
Mg	3.0–8.0
S	2.0–3.0
Fe	100–250
Mn	100–350
Zn	20–50
B	20–50
Cu	10–50
Mo	1–5

Source: Compiled from Small, H.G. and Ohlrogge, A.J., Plant analysis as an aid in fertilizing soybeans and peanuts, in *Soil Testing and Plant Analysis,* Walsh, L.M. and Beaton, J.D. (eds.), Soil Science Society of America, Madison, WI, 315–327, 1973.

[a] Concentration of macronutrients in g kg^{-1} and micronutrients in mg kg^{-1}.

TABLE 14.2
Yield and Total Nutrients Harvested in Two Peanut Genotypes at Two N Levels

		0 kg N ha^{-1}		200 kg N ha^{-1}		SE ±	
		Robut 33-1	Non-Nod	Robut 33-1	Non-Nod	[a]	[b]
Haulm (kg ha^{-1})		3249	1099	2660	1681	108.7	127.8
Pod (kg ha^{-1})		2099	553	2438	1053	267.9	198.4
Total nutrients harvested (kg ha^{-1})	N	176.6	23.9	143.9	51.3	11.98	8.47
	P	15.1	10.3	11.8	11.6	1.05	0.75
	K	55.0	21.0	43.0	35.0	3.88	2.74
	Ca	34.2	14.4	28.1	21.9	2.53	1.79
	Mg	27.0	7.3	24.0	15.0	2.25	1.59
	Fe	6.32	1.42	4.95	1.99	0.695	0.492
	Zn	0.25	0.12	0.19	0.15	0.019	0.013
	Mn	0.29	0.08	0.25	0.11	0.020	0.014

Source: Adapted from Sahrawat, K.L. et al., *Plant Soil,* 104, 291, 1988.

[a] Standard error of mean for comparison between the genotypes and the nitrogen levels.

[b] Standard error of mean for comparison between the nitrogen levels of the same genotype.

Nutrient uptakes (concentration × dry matter) by two peanut genotypes are presented in Table 14.2. The amounts of nutrient elements in the plant parts were the greatest for N, followed by K, Ca, Mg, P, Fe, Mn, and Zn in descending order (Sahrawat et al., 1988).

14.6 SUMMARY

The peanut is an important warm-season oilseed crop and food grain legume. It originated in the lowlands of South America and is now grown in the tropics, subtropics, and warm temperate regions worldwide. Approximately 94% of world peanut is produced in Asia and Africa, mostly under rainfed conditions. Peanut seeds contain about 50% oil and 25%–30% protein, and they make a substantial contribution to human nutrition.

Average growing season temperatures of 24°C–33°C are adequate for peanut production. The crop can grow on a wide range of soils, but well-drained sandy loams with adequate supplies of calcium are ideal. Peanut is very tolerant of acid soils, as long as adequate calcium is present in the surface soil to support peg and fruit development. It is intolerant of poor soil aeration and is moderately susceptible to salinity.

Under favorable conditions, symbiotic nitrogen fixation can account for much of the crop's nitrogen requirements. One metric ton of unshelled seeds removes approximately 40 kg N, 3 kg P, and 5 kg K. Since nitrogen fixation is normally significant, fertilizer requirements are modest compared with those of cereals. Both soil and plant analyses can be used to diagnose and correct nutrient deficiencies.

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15 Sugarcane

15.1 INTRODUCTION

Sugarcane is an important economic crop in the tropics and subtropics due to its high sucrose content and increasing interest in its bioenergy potential (Gilbert et al., 2007). Sugarcane (*Saccharum* spp. hybrid) is the world's most important sugar crop (Bakker, 1999; Cheeroo-Nayamuth et al., 2000). It is an erect, very robust, tillering, perennial C_4 grass. It is grown primarily for sugar (sucrose), but molasses, ethyl alcohol, and fiber (bagasse) are its important by-products. Commercial sugarcane cultivars are complex interspecific hybrids of up to five species of *Saccharum robustum*; *Saccharum sinense*; *Saccharum barberi*; *Saccharum officinarum*, the "noble" canes; and *Saccharum spontaneum*, a freely tillering wild species used as a source of vigor and disease resistance (Lingle and Tew, 2008; Wang et al., 2008). The "noble" canes may have been selected from *S. robustum* by stone-age cultures in New Guinea. They were spread throughout the Pacific and Southeast Asia prior to the arrival of European man. Cane was taken by the Spanish and Portuguese to the New World to form the basis of sugarcane culture in the sixteenth century. In the late eighteenth century, more desirable cultivars of *S. officinarum* were introduced. Modern sugarcane breeding began at the end of the nineteenth century, when viable true seeds were discovered (Jones, 1985).

Brazil, India, and China have the three largest sugarcane industries, producing 420, 232, and 89 million tons, respectively, in 2005. Other major producers (and their production in millions of tons in 2005) include Thailand (50), Pakistan (47), Mexico (45), Colombia (40), Australia (38), Philippines (31), and the United States (26) (FAO, 2009).

Brazil has a long tradition of growing sugarcane. In the sixteenth century, it was the world's major source of sugar (Courtenay, 1980; Hartemink, 2008). At present, sugarcane is also a major source of ethanol, and one hectare of sugarcane land with a yield of 82 Mg ha^{-1} produces about 7000 L of ethanol (Hartemink, 2008). Brazil currently produces about 31% of global production, and it is the largest producer, consumer, and exporter of ethanol for fuel (Andrietta et al., 2007; Hartemink, 2008). The value of sugar and ethanol industry reached about 17% of Brazil's agricultural output (Valdes, 2007; Hartemink, 2008). The cultivation of sugarcane for bioethanol is increasing and area under sugarcane is expanding in Brazil.

15.2 CLIMATE AND SOIL REQUIREMENTS

Sugarcane is adapted to a range of tropical and subtropical climates. It is grown from 37°N in southern Spain to 31°S in the Republic of South Africa. It cannot tolerate freezing temperatures, and growth essentially ceases at mean minimum temperatures below about 12°C (Ryker and Edgerton, 1931). Maximum photosynthetic rates occur at air temperatures of about 34°C (Alexander, 1973), and intact plants can survive temperatures in excess of 52°C (Irvine, 1983). The ideal climate for a 1 year crop would include at least 4–5 months with mean daytime temperatures of 30°C–35°C to stimulate growth and 1.5–2 months of cooler temperatures prior to harvest to enhance sucrose accumulation (Gascho and Shih, 1982).

Sugarcane is successfully grown under a wide range of temperature, solar radiation, rainfall, and soil conditions. If soil, water, and plant nutrition are adequate, temperature and/or solar radiation can be used to predict cane growth rates (Allen et al., 1978). When water is limiting, rainfall and/or irrigation may be correlated with yields (Early, 1974; Thompson, 1976; Jones, 1980). Limited water resources restrict the amount of sugarcane grown in many regions throughout the world because

sugarcane requires substantial amounts of water (Martin et al., 2007). Several studies have been conducted to determine the effect of different levels of water application on sugarcane (Wiedenfeld, 1995; Wiedenfeld and Enciso, 2008). In a 3 year flood-irrigated study, when water inputs were reduced by 25% and 43%, yield reductions averaged 30% and 53%, respectively (Wiedenfeld, 1995). Smaller variation in water inputs of <20%, however, has not always produced significant differences in sugarcane yields (Wiedenfeld, 2004). The evaluations of water stress during different stages of plant growth have indicated that while the effect of water stress may be similar during all growth stages (Wiedenfeld, 2000), sugarcane has the capacity to compensate for brief periods or water stress given enough time for growth; therefore, the impact of stress later in the growth cycle, but prior to ripening, may be more severe (Robertson et al., 1999; Inman-Bamber, 2004).

Sugarcane can be grown on a wide variety of soils (Johnson and Richards, 2005; Glaz and Gilbert, 2006; Suman et al., 2006). It can also tolerate soil pH values ranging from about 4 to 9, though nutritional problems may occur at the extremes. Although some cultivars tolerate moderate salinity and seasonal flooding, good drainage and salinity management are normally required for high yields. Sugarcane is considered moderately susceptible to soil salinity; the salinity threshold (initial yield decline) has been reported to be 1.7 dS m^{-1}, and the yield decrease per unit increase in salinity beyond threshold is 5.9% (Maas and Hoffman, 1977). Serious yield reductions occur at a conductivity of 4–8 dS m^{-1}, and very little cane growth or death occurs above 10 dS m^{-1} (Valdivia, 1981; Bresler et al., 1982).

15.3 GROWTH AND DEVELOPMENT

Sugarcane is propagated vegetatively by planting stem cuttings (setts), from which auxiliary buds grow to produce erect primary stalks (main stems). Secondary and tertiary stalks (tillers) are produced at the base of the primary stalk. Sugarcane produces multiple tillers, each having numerous nodes separated by internodes. The internodes consist of sucrose storing parenchyma cells and vascular tissue, with the stem being the major sink for photosynthates (sucrose) (Tejera et al., 2007). Sugarcane leaf laminae are 700–1200 mm long and up to 100 mm wide. Internodes are up to 250 mm long and 20–60 mm in diameter. Only about 10 fully expanded leaves are usually present on a stalk because both lamina and sheath are shed when they senesce. The inflorescence, a panicle (also known as the arrow or tassel), is produced under certain environmental conditions. Genotype, photoperiod, temperature, nutrition, and water stress all affect panicle initiation and growth. Since the stalk ceases to grow and sucrose content declines after flowering, genotypes that flower readily under field conditions are avoided (Clements, 1980).

Maximum dry matter accumulation occurs only with near-optimum temperatures, high solar radiation, complete ground cover, and minimal nutrient and water stresses. Under these conditions, short-term (1–2 months) production of aboveground biomass can reach 40–44 g m^{-2} day^{-1} (Thompson, 1978; Shih and Gascho, 1981; Irvine, 1983). The incomplete interception of light during canopy development, low solar radiation, suboptimal temperatures, reduced growth during ripening, and a variety of soil and biotic stresses typically reduce the full-season growth rates of commercial fields and experimental plots to 6–25 and 20–32 g m^{-2} day^{-1}, respectively (Irvine, 1983).

15.3.1 Shoots

Since flowering is normally suppressed in commercial sugarcane crops, the growth stages used to describe the crop relate to more or less distinct periods of vegetative growth: germination and emergence, tillering and canopy establishment, grand growth, and ripening (Gascho and Shih, 1982). The duration of the stages is highly dependent on climate. Low temperatures or drought stress can delay germination, emergence, tillering, and canopy development. In subtropical climates, the first two stages may last up to 5 months, and warm temperatures and plentiful water and nutrients can promote vegetative growth and delay ripening. In Hawaii, where cane

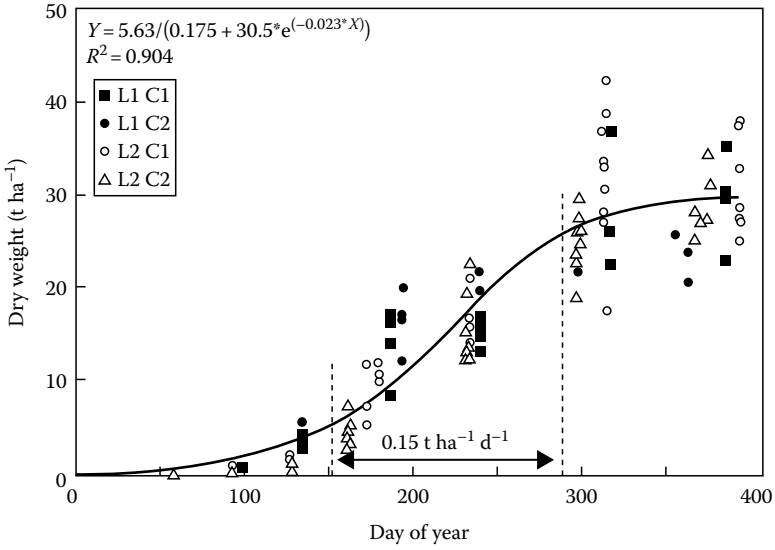

FIGURE 15.1 Dry weight accumulation by sugarcane grown on organic soils of the Everglades agricultural area (L1, location 1; L2, location 2; C1, crop 1; C2, crop 2). (From Coale, F.J. et al., *Agron. J.*, 85, 310, 1993. With permission.)

is grown for 2 years, the grand growth period can be extended by providing adequate water and nutrients until the crop is 20–22 months old.

Sugarcane has the capacity to tiller rapidly. Under favorable growing conditions, stem numbers increase exponentially with time until a maximum of 20–30 stalks m^{-2} is reached at 4–6 months (Gosnell, 1968; Bull and Glaziou, 1975). Leaf area index (LAI) increases in a similar exponential manner. When LAI approaches 2.0–3.0 at 4–6 months, many younger tillers begin to die due to shading by older tillers, and tiller number normally stabilizes at 10–20 stems m^{-2}.

Several studies suggest that the maximum LAI for sugarcane is 7 to more than 8 m^{-2} leaf m^{-2}, but more common values lie between 4 and 5 (Bull and Tovey, 1974; Irvine and Benda, 1980; Irvine, 1983; Cock, 2003). The LAI typically declines as the crop approaches harvest maturity (Gosnell, 1968; Glover, 1972; Bull and Tovey, 1974), especially when nitrogen and water stresses or chemical ripeners are used to slow expansion growth and increase sugar storage in the stem.

In Florida, the grand growth period (GGP) for sugarcane is usually defined as beginning June 1 (152nd day of year) and ending October 15 (288th day of year). Coale et al. (1993) studied the dry weight accumulation of two sugarcane crops, each grown at two locations in Florida. Dry matter accumulation models for locations (L1 or L2) or crops (C1 or C2), or combination of location and crop (L1 C1, L1 C2, etc.) were not significantly ($P < 0.05$) different. Therefore, data from both locations and crops were used, and a logistic growth model was developed (Figure 15.1). Over the four crop years of this study, dry weight accumulation averaged 0.15 Mg ha^{-1} d^{-1} during the GGP. During this period of rapid growth, 64% of total crop dry matter was produced (Coale et al., 1993).

15.3.2 Roots

The early growth of sugarcane roots has been described by Clements (1980), Dillewijn (1952), and Glover (1967). Under favorable environmental conditions, the axillary buds on setts become active within 3 days of planting, and sett roots begin to grow from the root band at the base of the internode. Sett roots grow at a maximum rate of 24 mm day^{-1} and stop elongating when they are 150–250 mm long. They turn dark, decompose rapidly, and disappear within 2 months after planting. Shoot roots begin to grow from the short basal internodes of the shoot at about the time it emerges from the soil.

The first shoot roots are much thicker than the sett roots, their rate of growth is more rapid, they produce few branches, and they penetrate the soil at a steep angle.

Shoot roots produced later are finer and branch more freely than earlier shoot roots. Their maximum growth rate is 75 mm day^{-1} for periods of 1–2 days or 40 mm day^{-1} when their growth is averaged over a week (Glover, 1967). Wood and Wood (1968) used radioactive phosphorus uptake from different depths of a deep sandy soil and concluded that the rooting front reached 0.9 m in 112 days, 1.5 m in 161 days, and 2.1 m in 189 days.

The distribution of roots in the soil is strongly dependent on soil characteristics, cultivars, and soil water content. For example, Paz-Vergara et al. (1980) reported that for 11 furrow-irrigated fields in Peru, the percentage of roots in the 0.30 m horizon was 48%–68%; from 0.3 to 0.6 m, 16%–36%; from 0.6 to 0.9 m, 3%–12%; from 0.9 to 1.20 m, 4%–7%; from 1.2 to 1.5 m, 1%–7%; and from 1.5 to 1.8 m, 0%–4%.

Short irrigation intervals encourage roots to develop near the soil surface (Baran et al., 1974; Kingston, 1977). However, poor soil aeration restricts root growth. For example, Gosnell (1971) reported that sugarcane roots stop growth 50–100 mm above the water table. Root systems growing in deep sands tend to be finer, more highly branched, and deeper than those growing in heavy clay soils (Lee, 1926c; Glover, 1968; Thompson, 1976). For example, Glover (1968) found an extensive, fine, well-branched root system to extend more than 140 cm in sand. In a disturbed clay soil, the thick primary root system was well developed, but secondary branches were poorly developed. In an undisturbed clay soil, even the primary roots were poorly developed below the plow layer.

Genotypic variation in sugarcane root systems is well documented (Lee, 1926a,b; Dastane, 1957; Raheja, 1959). Some cultivars produce roots with a higher degree of branching than others (Stevenson and McIntosh, 1935). Root gravitropism also varies among cultivars, and cultivars with weakly gravitropic (more horizontal) root orientation are more resistant to lodging than other cultivars (Stevenson and McIntosh, 1935; Mukerji and Alan, 1959).

Environmental conditions can affect the expression of genotypic differences in root growth. For example, Rostron (1974) reported that the root distributions of two cultivars were similar under good conditions but differed under dry conditions. The development of adventitious roots in response to flooding is thought to be a tolerance mechanism to increase root aeration that allows the plant to maintain root function during flooding (Kovar and Kuchenbuch, 1994; Glaz et al., 2004a,b; Gilbert et al., 2007). These aboveground roots tend to grow horizontally to remain near the water–air interface. Aerenchyma formation in adventitious roots in response to flooding has been reported in a range of wetland and dryland grass species (McDonald et al., 2002).

15.4 CROP CULTURE

Cultural practices associated with sugarcane production vary widely as a result of economic, social, climatic, and soil conditions. In areas with high labor costs, essentially all cultural practices are mechanized. In other areas, a great deal of hand labor continues to be used.

Land preparation varies with soil type. Deep plowing, deep ripping, or subsoiling is often used to disrupt compacted layers. Soil may be formed into beds approximately 1.5 m apart to facilitate furrow irrigation, to improve surface drainage, or both. However, such beds increase land preparation costs and, where possible, flat culture is used.

15.4.1 Planting

Although sugarcane can be grown from true seed, commercial plantings are always made using stem cuttings or setts, often called seed (Cock, 2003). Setts with two or more buds are cut by hand or mechanically, often from special areas maintained to minimize disease infestation. Setts may receive hot water and/or fungicide treatments to further reduce disease problems. They are planted in furrows and are covered with soil. Time to sprouting differs among cultivars and is temperature

dependent, occurring after approximately 35 degree-days using a base temperature of 9°C (Keating et al., 1999). Fertilizer may be applied broadcast, in the furrow, or through the irrigation system. In areas where poor drainage is common, the setts are planted on top of beds. Where furrow irrigation is used, they are often planted in the furrows between beds. Flat culture is practiced whenever possible to reduce land preparation. Ratoon tillage operations are designed to remove postharvest compaction between rows and to control weeds.

In much of the world, sugarcane row spacing is about 1.5 m to facilitate mechanization. However, work on row spacing in Louisiana (Irvine and Benda, 1980) and Florida (Shih and Gascho, 1980; Gascho and Shih, 1981) suggests that narrow row spacing could result in more rapid canopy development, increased light interception, and higher yields in areas with short growing seasons.

15.4.2 Water Requirements, Irrigation, and Drainage

The sugar industries in Hawaii, Florida, Australia, South Africa, and Taiwan have historically relied on pan evaporation as an indicator of potential evapotranspiration (ET). Several studies suggest that potential ET from a well-developed sugarcane canopy during the grand growth stage is approximately equal to evaporation from a standard U.S. Weather Bureau class A pan (Thompson et al., 1963; Thompson, 1965; Hardy, 1966; Ekern, 1971; Fogliata, 1974). When calculated on a monthly basis, the ratio of ET to pan evaporation usually varies from 0.8 to 1.2, even though ratios as low as 0.63 and as high as 1.59 have been reported (Kingston and Ham, 1975).

Low ratios of potential ET to pan evaporation are often, though not always, found as the crop nears maturity in winter months (Moberly, 1974; Kingston and Ham, 1975; Thompson, 1976) and in ratoon crops (Hardy, 1966; Moberly, 1974; Thompson, 1976; Shih and Gascho, 1980), presumably due to the greater stomatal resistance of slowly growing crops (Thompson, 1986). Lodging can reduce ET up to 30% until a uniform canopy is reestablished (Ekern, 1971).

Transpiration is strongly affected by the amount of solar radiation intercepted by the crop canopy. When the soil surface is dry, actual ET is limited by canopy cover. For example, Chang et al. (1965) and Ekern (1971) reported that actual ET of adequately watered sugarcane increases from 0.3 to 0.6 of pan evaporation during the first month after planting to 0.8–1.0 of pan evaporation at 4–5 months. Kingston (1973) recommends using pan factors of 0.4, 0.6, 0.8, 0.9, and 1.0 for ground cover fractions of 0–0.25, 0.25–0.50, 0.50–0.75, 0.75–1.0, and 1.0, respectively.

If the crop canopy is complete, ET proceeds at the potential rate until 60%–70% of the total plant-extractable water is removed from the soil profile (Moberly, 1974; Koehler et al., 1982). Thereafter, the ratio of ET to potential ET declines until ET ceases in the completely senescent crop. Soil type strongly affects the amount and distribution of plant-extractable water in the soil profile. For example, Gosnell and Thompson (1965) found that sugarcane extracted water to at least 2.2 m in one soil. However, more water was extracted deep in a sandy soil profile than deep in a sandy loam or a shallow clay loam overlying decomposing shale (Hill, 1966; Thompson et al., 1967). Several other factors, including subsoil aluminum toxicity, presence of layers with high soil strength, or fragmental or cemented horizons, can limit root growth in the subsoil, thereby reducing water available for transpiration and increasing the susceptibility of the crop to drought stress.

Sugarcane is most susceptible to drought stress during the first 3–4 months after planting, when severe stress can reduce stands and make replanting necessary. During tillering and canopy development, young tillers are more susceptible to drought than the main stem or older tillers. Leaves on young tillers begin to roll earlier than those on the primary stem, probably due to the less-developed root systems of the tillers (Clements, 1980). After a tiller begins to produce elongated internodes, the rate of stem elongation and final internode lengths are the convenient means of assessing the effects of drought stress. Internodes that elongate during stress are permanently shortened relative to those of well-watered plants, and they serve as a record of the timing, length, and severity of drought stress.

Drought stress has long been known to increase nonstructural carbohydrates in sugarcane leaves and stems (Clements and Kubota, 1943). For example, early morning total sugar concentration of

young leaf sheaths falls as low as 5% in rapidly growing, well-watered plants; however, it frequently increases to more than 10% during drought stress. High correlations are found among leaf sheath water content and leaf nitrogen and potassium concentrations (Samuels et al., 1953; Samuels, 1971; Clements, 1980). All decrease during drought stress, and in some areas, plant analyses used to detect nitrogen and potassium deficiencies are adjusted to take tissue water content into account (Clements, 1980).

Irrigation by flooding, furrow, sprinklers, drip (trickle), and subirrigation (by water table adjustment) are all used for sugarcane. Several reviews of sugarcane irrigation practices are available (Gosnell and Pearse, 1971; Gibson, 1974; Leverington and Ridge, 1975; Thompson, 1977; Finkel, 1983). Four methods have been widely used to schedule irrigation: resistance blocks, tensiometers, the water balance, and tissue moisture content. All are based on their ability to predict when incipient drought stress will occur, usually as indicated by a decrease in stem or leaf elongation. Experiments that compare cane and sugar yields from plots irrigated with different frequencies and/or amounts are used to validate these methods. Regardless which method is used to select ideal irrigation schedules, actual irrigation practices are modified in response to availability of water, personnel, and equipment.

Jones (1980) analyzed several irrigation experiments conducted in Hawaii. After eliminating treatments in which excessive water had reduced yields, presumably due to poor soil aeration and/or leaching of nutrients, a linear relationship was found between relative water use (RWU, the ratio of effective water applied to class A pan evaporation) and relative cane yield (Y, the ratio of actual yield to maximum yield in the experiment) in three experiments:

$$Y = 1.01\mathrm{RWU} + 0.03 \quad (R^2 = 0.90, n = 14)$$

Thompson (1976) selected data from studies in South Africa (Thompson and Boyce, 1967, 1968, 1971; Thompson and De Robillard, 1968; Boyce, 1969), Australia (Kingston and Ham, 1975), Hawaii (Campbell et al., 1959), and Mauritius (Hardy, 1966), for which ET had been estimated. For total crop ET ranging from 66 to 384 mm and cane yields (Y) ranging from 57 to 342 Mg ha^{-1}, he found the following relationship:

$$Y = 0.969\mathrm{ET} - 2.4 \quad (R^2 = 0.90, n = 91)$$

The slope of the relationship is similar to that reported by Jones (1980) for furrow- and sprinkler-irrigated experiments in Hawaii (1.03 Mg cane cm^{-1} effective water).

In many areas, sugarcane is grown on nearly level soils in which the water table reaches the root zone during at least part of the year. In Louisiana, sugarcane is grown on low, nearly level land near large bodies of water. High water tables are common, especially during the winter months, when sugarcane leaf area and ET are low. In such cases, response to supplemental irrigation is rare (Carter and Floyd, 1973), probably because the crop can extract much of its water requirement from the water table. A similar situation occurs in western Taiwan, where water tables frequently rise near the soil surface in the rainy season. In the dry season, the crop obtains 25%–50% of its water requirement from a water table at approximately 1.6 m. This dramatically reduces irrigation demands (Yang and Chang, 1976; Hunsigi and Srivastava, 1977; Chang and Wang, 1983).

The most important use of water tables for irrigation occurs on organic soils of the south Florida Everglades. During the dry season, growers pump supplemental water from a primary canal system into a system of farm canals, lateral ditches, and field ditches. The lateral movement of water from the field ditches into the field is often facilitated by mole drains 15 cm in diameter, 70–90 cm deep, and 2–3 m apart. The organic soils in this region are quite permeable, lateral movement is rapid, and the water table can easily be raised to provide supplemental water.

If the water table remains near the soil surface, poor aeration may cause setts to decay, reduce ratoon stalk populations (Carter et al., 1985), reduce root growth (Banath and Monteith, 1966; Gosnell, 1971), and cause the cane to produce aerotropic (Srinivasan and Batcha, 1962) or floating (Sartoris and Belcher, 1949) roots. Rudd and Chardon (1977) reported a yield decline of 0.46 Mg cane ha^{-1} for each day the water table rose above 0.5 m.

Louisiana sugarcane farmers plant cane on high (0.30–0.45 m) ridges 1.8 m apart to enhance surface drainage and provide a small volume of aerated soil at almost all times. When winter rainfall is relatively low, these practices provide adequate aeration, but in many years, excess rainfall raises water tables and reduces yields (Carter and Floyd, 1975; Carter, 1977a; Carter and Camp, 1983).

A 7 year lysimeter study on fine-textured Louisiana soils indicated that drainage systems should reduce the water table to 1.2 m within 4 days in order to maximize cane and sugar yields (Carter, 1977b). This maintains high redox potentials in the upper 0.5 m of soil (Carter, 1980), allows good ratoon growth early in the spring, and increases stalk populations.

Sugarcane cultivars differ in sensitivity to high water tables (Srinivasan and Batcha, 1962; Andreis, 1976). Cultivars tolerant to waterlogging respond with the production of aerotropic or floating roots (Shah, 1951; Srinivasan and Batcha, 1962). Some Florida cultivars exhibit better growth with water tables at 0.32 m than at 0.61 or 0.84 m; however, the growth of other cultivars is greatly inhibited by the 0.32 m water table (Gascho and Shih, 1979).

15.4.3 Nutrient Requirements

Because of its long growing season and high maximum growth rate, sugarcane has large nutrient requirements, but since it is a high-value crop, most sugarcane industries apply large amounts of fertilizers in an attempt to avoid nutrient deficiencies. Both soil and plant analyses have long been used to assess crop nutrition and soil fertility. Nitrogen requirements of sugarcane in South Texas have been found to be very low in the plant crop and increase in each second and subsequent ratoons (Wiedenfeld and Enciso, 2008). Soil testing for NO_3–N has not been found to be a useful indicator of sugarcane responses to N fertilization in this subtropical environment (Wiedenfeld and Enciso, 2008). Coale et al. (1993) studied the N, P, K, Ca, and Mg seasonal accumulation patterns by sugarcane grown on organic soils of the Florida Everglades (Figures 15.2 through 15.5). Nitrogen accumulation closely paralleled biomass accumulation (Figure 15.2). During the grand growth period, N uptake averaged 0.67 kg ha^{-1} d^{-1} and accounted for 54% of total N accumulation. However, the organic soils on which these experiments were conducted had been artificially drained, greatly increasing their rate of mineralization, and the average N uptake during the grand growth period was equivalent to only 15% –20% of the estimated rate of soil N mineralization (Terry, 1980).

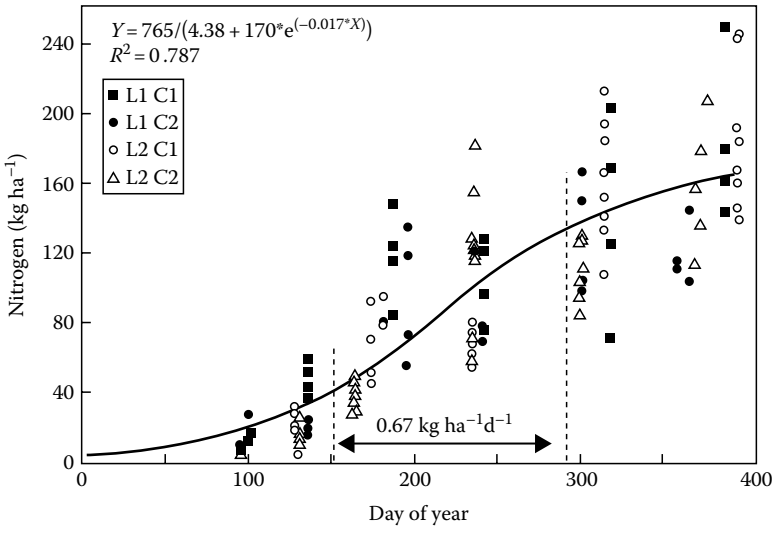

FIGURE 15.2 Nitrogen accumulation by sugarcane grown on organic soils of the Everglades agricultural area (L1, location 1; L2, location 2; C1, crop 1; C2, crop 2). (From Coale, F.J. et al., *Agron. J.*, 85, 310, 1993. With permission.)

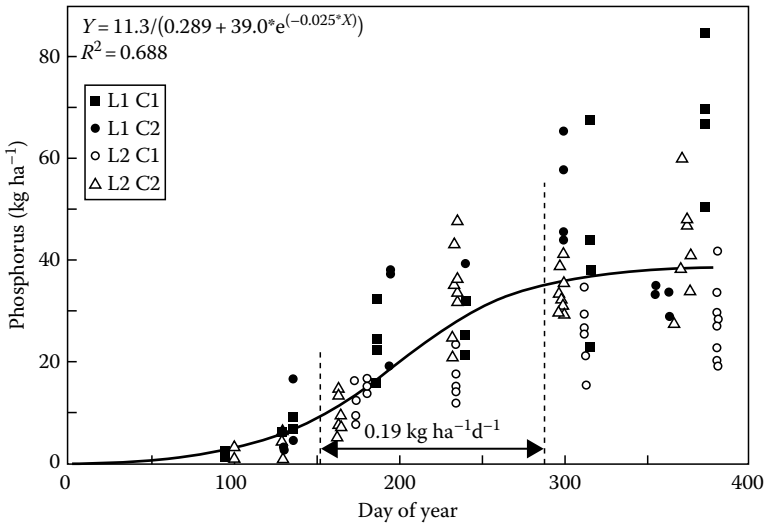

FIGURE 15.3 Phosphorus accumulation by sugarcane grown on organic soils of the Everglades agricultural area (L1, location 1; L2, location 2; C1, crop 1; C2, crop 2). (From Coale, F.J. et al., *Agron. J.*, 85, 310, 1993. With permission.)

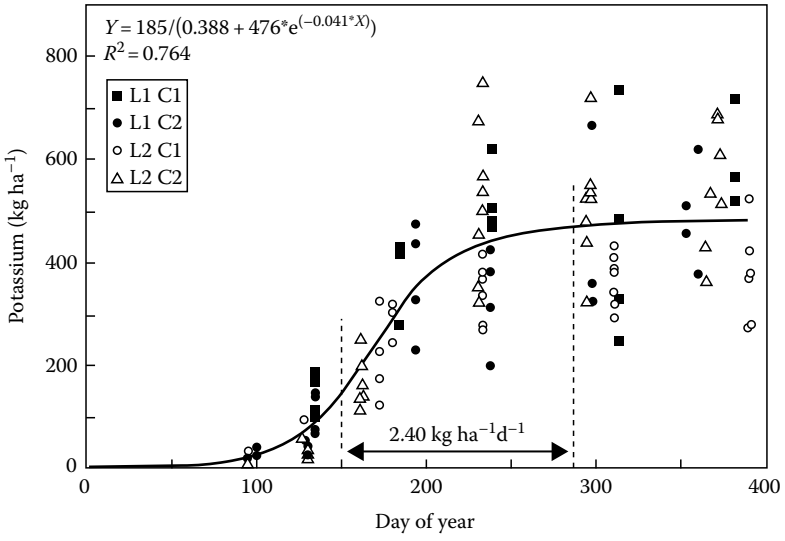

FIGURE 15.4 Potassium accumulation by sugarcane grown on organic soils of the Everglades agricultural area (L1, location 1; L2, location 2; C1, crop 1; C2, crop 2). (From Coale, F.J. et al., *Agron. J.*, 85, 310, 1993. With permission.)

At harvest, 71% of total dry matter and 55%, 63%, 64%, 25%, and 38% of total accumulated N, P, K, Ca, and Mg, respectively, were removed from the field as millable sugarcane. Because of the rapid mineralization of soil organic matter, little fertilizer was required, and P and K removed from the field at harvest were 179% and 201%, respectively, of fertilizer P and K.

Positive yield responses to P and K fertilization of sugarcane grown on organic soils have been documented (Gascho and Kidder, 1979). Glaz et al. (2000) reported that sugarcane genotypes differ significantly in response to P fertilization. Seasonal P and K accumulation were also described by logistic models (Figures 15.3 and 15.4, respectively). Phosphorus and K uptake during the grand growth period contributed 67% and 68% of total P and K accumulation, respectively. The K uptake rate was very high (4.14 kg ha^{-1} d^{-1}) during the first 60 days of the period.

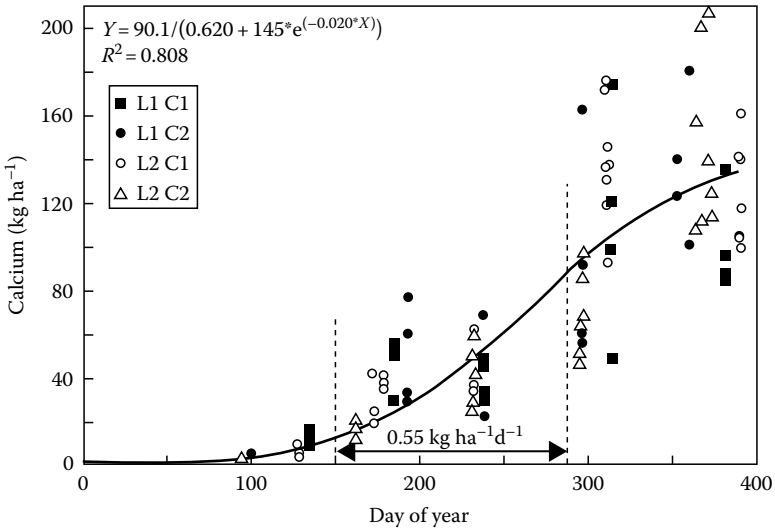

FIGURE 15.5 Calcium accumulation by sugarcane grown on organic soils of the Everglades agricultural area (L1, location 1; L2, location 2; C1, crop 1; C2, crop 2). (From Coale, F.J. et al., *Agron. J.*, 85, 310, 1993. With permission.)

Phosphorus and K fertilizers are normally applied at the time of planting for plant-cane crops and after initiation of ratoon regrowth for ratoon crops. For optimum sugarcane production on organic soils, fertilizer applications of 0–37 kg P ha^{-1} and 0–233 kg K ha^{-1} are recommended, depending on soil-test-extractable P and K determined prior to planting (Sanchez, 1990).

Calcium accumulation by sugarcane was described by a logistic model similar to the models derived for N, P, and K uptake (Figure 15.5). One notable difference was the absence of a well-defined stationary phase for crop Ca accumulation at crop maturity. As with the other macronutrients, Mg uptake was most rapid during the grand growth period, when 62% of total crop Mg accumulation occurred (Figure 15.6).

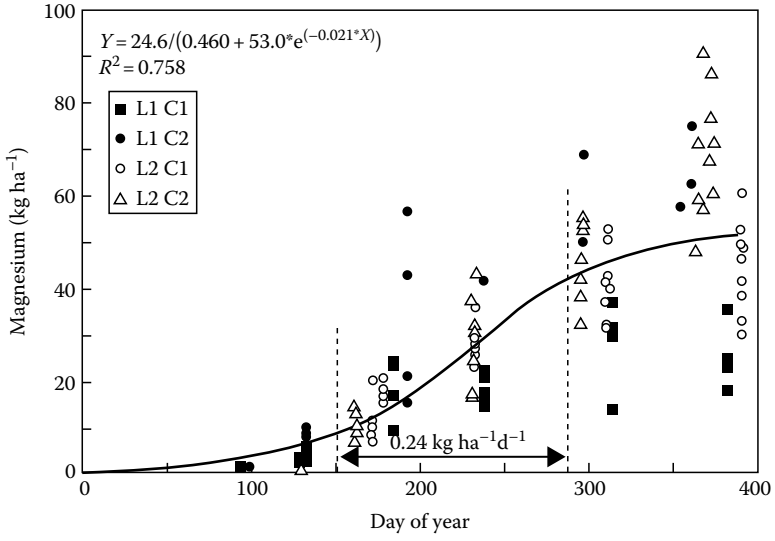

FIGURE 15.6 Magnesium accumulation by sugarcane grown on organic soils of the Everglades agricultural area (L1, location 1; L2, location 2; C1, crop 1; C2, crop 2). (From Coale, F.J. et al., *Agron. J.*, 85, 310, 1993. With permission.)

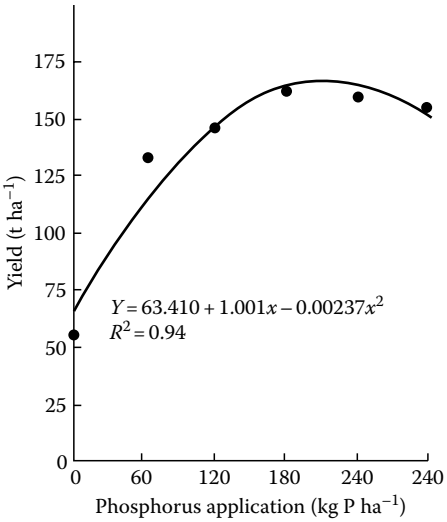

FIGURE 15.7 Sugarcane yield as a function of phosphorus rates in a Brazilian Vertisol. Regression equation values of P are expressed as P_2O_5. (From Pereira, J.R. et al., *Pesq. Agropec. Bras. Brasilia*, 30, 43, 1995. With permission.)

Barnes (1974) reported removal of 0.7–0.9 kg N, 0.22–0.26 kg P, and 1.28 kg K per ton of cane. In contrast, for a 2 year old crop in Hawaii, nutrient accumulation values (Clements, 1980) per ton of cane were 0.48 kg N, 0.09–0.33 kg P, and 0.75 kg K. These differences may be accounted for by the amount of trash (leaves and roots) transported to the mill, age of sugarcane at harvest, and nutrient uptake differences among cultivars (Gascho et al., 1993). Pereira et al. (1995) studied the relationship between P rates and sugarcane yield in a Brazilian Vertisol (Figure 15.7). The maximum yield was obtained at about 92 kg P ha^{-1}.

Table 15.1 gives adequate levels of sugarcane nutrient concentrations. As with other crops, sugarcane nutrient concentrations vary with age and among plant parts. The highest shoot N concentrations occur in young plants and tillers. The concentration declines with age due to the production of internodes with low N concentrations (Table 15.2). As leaves age, their N concentrations decline due to the production of structural tissues and the retranslocation of nutrients to active meristems. For example, Ayers (1936) reported that N concentration declines from 1.2% in the youngest leaves to about 0.4% in the oldest green leaves and 0.2% in senescent leaves still attached to the plant.

Environmental conditions that reduce crop growth can cause tissue N concentrations to increase. Thus, cool wet weather often results in higher N concentrations than normal (Dillewijn, 1952; Clements, 1980). Nitrogen deficiency has several effects on sugarcane growth. Leaf expansion decreases, the interval of leaf appearance increases, and leaf senescence increases. Thus, N-deficient sugarcane tillers may have only 4–6 green leaves instead of the 12–14 that are found on normal tillers (Clements, 1980). Photosynthesis is less sensitive to N stress than expansion growth. As a result, sucrose accumulates in the leaves and internodes of N-deficient sugarcane, and fertilizer N is normally withheld from sugarcane prior to harvest in order to increase stalk sucrose concentration (Clements, 1980).

Growing plant meristems need a continuous supply of P for incorporation into new tissue. Soil P supply is not constant due to variation in soil water content and root development; therefore, plants have developed mechanisms for taking up and storing excess P and subsequently using it for new growth. Sugarcane accumulates inorganic P in the stem when the soil P supply permits. During periods of inadequate uptake, this inorganic P can be translocated to meristematic tissues (Hartt, 1972). Since much of the P in sugarcane internodes is in the highly mobile inorganic form, internode P concentration is more sensitive to P nutrition than is leaf P, which is predominantly organic (Hartt, 1972).

TABLE 15.1
Adequate Concentration of Nutrients in Sugarcane Plants

Nutrient	Growth Stage[a]	Plant Part[a]	Adequate Concentration g kg^{-1}
N	3 months (plant)	TVD	24–25
	6 months (plant)	TVD	19
	3 months (plant)	TVD	21
	4–5 months (ratoon)	TVD	19
	Early rapid growth	Leaves 3–6	15–27
P	3–6 months (plant)	TVD	2.1–3.5
	10.3 months (plant)	3rd LB below A	2.1–3.0
	2–4.5 months (ratoon)	TVD	2.1–3.5
	7 months (ratoon)	3rd LB below A	2.1–3.0
	Early rapid growth	Sheath 3–6	0.5–2.0
K	3–6 months (plant)	TVD	12.5–20.0
	10.3 months (plant)	3rd LB below A	13.0–20.0
	2–4.5 months (ratoon)	TVD	12.5–20.0
	6–7 months (ratoon)	TVD	11.0–18.0
	Early rapid growth	Sheath 3–6	22.5–60.0
	7–14 months (plant)	Internodes 8–10	10.0
Ca	3 months (plant)	TVD	1.4–1.8
	4.5–6 months (plant)	TVD	1.5–2.0
	2–3 months (ratoon)	TVD	1.6–2.0
	5 months (ratoon)	TVD	2.0–2.4
	Early rapid growth	Sheath 3–6	1.0–2.0
Mg	3 month (plant)	TVD	0.9–1.2
	4.5–6 months (plant)	TVD	1.2–1.8
	2–3 months (ratoon)	TVD	1.0–1.8
	5 months (ratoon)	TVD	1.2–1.8
	Early rapid growth	Sheath 3–6	1.5–10.0
S	35 DAS	Sheath 3–6	6.1
	70 DAS	Sheath 3–6	0.8
	7 months	TVD	1.3
			mg kg^{-1}
Cu	Rapid growth	TVD	4.0–15.0
	6–7 months (ratoon)	TVD	4.2–12.2
	Rapid growth	Blades 3–6	5.0–100.0
Zn	Rapid growth	TVD	15.0–50.0
	6–7 months (ratoon)	TVD	12–50
	Rapid growth	Blades 3–6	20–100
Mn	Rapid growth	TVD	20–200
	6–7 months (ratoon)	TVD	15–200
	Rapid growth	Blades 3–6	20–400
Fe	Rapid growth	TVD	5–100
	7 months	TVD	49–915
	Rapid growth	Blades 3–6	20–600
B	Rapid growth	TVD	2–10
	7 months	TVD	1.6–10
	Rapid growth	Blades 3–6	2.0–30

(*continued*)

TABLE 15.1 (continued)
Adequate Concentration of Nutrients in Sugarcane Plants

Nutrient	Growth Stage[a]	Plant Part[a]	Adequate Concentration mg kg^{-1}
Mo	Rapid growth	TVD	0.08–1
	Rapid growth	Blades 3–6	0.05–4.0

Source: Compiled from Reuter, D.J., Temperate and subtropical crops, in *Plant Analysis: An Interpretation Manual*, Reuter, D.J. and Robinson, J.B. (eds.), Inkata Press, Melbourne, Australia, 38–99, 1986.

[a] DAS, days after sowing; TVD, top visible dewlap, which is approximately the third leaf from the shoot apex; LB, leaf blade (excluding sheath); A, apex.

TABLE 15.2
Tissue Nitrogen Concentration of Sugarcane in Hawaii at 12 Months of Age

Plant Part	N Concentration (g kg^{-1})
Meristem	17.7
Young blades	11.8
Old blades	8.9
Young sheaths	4.5
Old sheaths	3.1
Internodes	
10–12	1.7
7–9	1.1
4–6	1.4
1–3	1.5

Source: Modified from Clements, H.F., *Sugarcane Crop Logging and Crop Control: Principles and Practice*, University of Hawaii Press, Honolulu, HI, 1980.

As in the case of N, shoot P concentration decreases with age as a result of a decrease in the ratio of meristematic tissues with high P concentrations to structural tissues with low P concentrations (Clements, 1980). The concentration of K in sugarcane varies among plant parts and with time (Tables 15.1 and 15.3). Since K remains largely in solution rather than immobilized in protein or structural components of the cell, Clements (1980) proposed that sugarcane K concentration be expressed as a percentage of tissue water content rather than dry weight.

Unlike some grain crops, the K content of sugarcane stalks increases steadily with time, and older stalk internodes usually contains greater K concentrations than younger internodes (Table 15.3) (Jones, 1985). Since whole sugarcane stalks (sometimes including leaves) are removed from the field, sugarcane has a high fertilizer K requirement. Most of the K removed from the field in the cane stalks is concentrated in the molasses; therefore, little is returned to the field in filter mud, bagasse, or furnace ash.

The effect of plant age on sugarcane Ca concentration has long been recognized. Gosnell and Long (1971) reported that in Uganda, the Ca content of the youngest fully expanded leaf decreases from 0.37% at 1 month to 0.25% at 5 months. Similarly, in Hawaii, the Ca content of immature sheaths declines from above 0.3% in the first 4 months to below 0.2% after 18 months (Bowen, 1975). Drought stress tends to increase the Ca concentration of leaf tissues (Gosnell and Long, 1971).

TABLE 15.3
Typical Potassium Concentrations of Sugarcane Tissues Prior to Harvest

Plant Part	K Concentration (g kg^{-1})
Meristem and expanding cane	35.5
Young blades	16.5
Old blades	13.1
Young sheaths	24.8
Old sheaths	20.5
Internodes	
45–47	10.7
24–26	7.5
1–3	7.2

Source: Modified from Clements, H.F., *Sugarcane Crop Logging and Crop Control: Principles and Practice*, University of Hawaii Press, Honolulu, HI, 1980.

In Hawaii, Florida, and several other parts of the world, sugarcane is grown on highly weathered or organic soils that are low in soluble silicates. Plant silicon occurs in the form of opal ($SiO_2 \cdot nH_2O$) and plays a role in strengthening cell walls. As the plant ages, total Si concentrations of blades and sheaths increase as uptake, translocation, and deposition occur. The total Si concentration of leaf sheaths is normally higher than that of blades, and the highest concentrations are found in the leaf tip and margins, where trichomes and marginal sclerenchyma are heavily silicified.

Si-deficient plants develop small, elongated, chlorotic spots on the leaves. These spots eventually coalesce, and affected leaves die prematurely. Calcium silicate can be applied to provide adequate soluble Si for plant growth, and nearly twofold increases in cane yields have been attributed to the addition of silicates (Elawad et al., 1982a,b).

15.4.4 Biological Nitrogen Fixation

Dobereiner (1961) determined in the late 1950s that N_2-fixing bacteria of the genus *Beijerinckia* are present in the rhizosphere of sugarcane. Most of the research work on N_2-fixation in sugarcane has been conducted in Brazil, where about 17% of total plant N at harvest is attributed to N fixation, equivalent to 17 kg ha^{-1} of N at yields of 70 Mg ha^{-1} (Ruschel and Vose, 1982; Hartemink, 2008). Recent studies suggest that some Brazilian sugarcane cultivars can fix over 200 kg N ha^{-1} (Medeiros et al., 2006; Oliveira et al., 2006). Nitrogen fixation is high for most Brazilian cultivars as they have been systematically bred for high yields with low N inputs (Boddey et al., 1995). For example, depending on the yield, 100–200 kg N ha^{-1} is removed with the cane at harvest, but annual N application rates on sugarcane in Brazil average only 50 kg N ha^{-1} (FAO, 2004). If over 200 kg N ha^{-1} year^{-1} is fixed biologically, it can be assumed that N concentrations in Brazilian sugarcane soils will not decrease with time (Boddey et al., 2003).

15.4.5 Ripening

The ripening of sugarcane refers to the gradual increase in stalk sucrose content (on a dry weight basis) as harvest approaches. Legendre (1975) defined ripening of sugarcane as an increase in sucrose yield per Mg ha^{-1} of harvested cane. Numerous studies have shown that cool temperatures, high solar radiation, moderate nitrogen and/or drought stress, and use of chemical ripeners can stimulate ripening (Lonsdale and Gosnell, 1974; Mason, 1976; Rostron, 1977; Clowes and Inman-Bamber, 1980). The combined stresses reduce expansion growth before they reduce photosynthesis

(Inman-Bamber and de Jager, 1986a,b). Therefore, more sucrose is available for translocation to storage tissues in the stem, and the total amount of sucrose in the crop increases.

15.4.6 Harvest and Ratoon Growth

Sugarcane is normally grown as a perennial crop and is harvested several times before replanting. The first cycle is referred to as the plant crop and subsequent crops as ratoons (Cock, 2003). Cane fields are often burned before harvest to reduce the amount of trash and green leaves hauled to the mill. Harvesting may be labor intensive or highly mechanized. Good harvesting systems minimize cane breakage, transport little trash and other extraneous material to the mill, and minimize the time between harvest and cane processing. Cane that is left in the field after burning or cutting soon begins to deteriorate in quality, reducing sugar recovery in the mill.

Some sugar industries throughout the world are adopting green-cane harvesting, mainly due to public pressure to reduce smoke from burning, but also because burning can reduce total sugar recovery at the mill, reduce organic matter in the soil, and increase erosion and water pollution (Richard et al., 2001; Sampietro and Vattuone, 2006; Viator et al., 2006). For many years, manual harvest of unburned cane has been practiced in South Africa, where cane tops are left on the soil surface to conserve moisture and control erosion. With green-cane harvesting, 6–24 Mg ha^{-1} of postharvest residue, regardless of whether the sugarcane is manually or mechanically harvested, is deposited on the field surface (Viator et al., 2006). The mechanized harvest of unburned cane is practiced in Australia and some other areas, where cane trash is left in the field to conserve soil moisture and prevent erosion.

At harvest, the dry weight of a sugarcane stem usually consists of about 50%–60% millable cane, 30%–40% tops (leaves and immature stem), and 10% roots and stubble. Crops grown for more than 1 year, as in Hawaii, have much longer stems and usually have higher percentages of millable cane. Of the millable cane's fresh weight, about 70% is water. Of its dry weight, about 50% is sucrose. The percentage of sucrose in sugarcane juice, usually referred to as the polarization value (Pol), varies from 8% to 15% (Tewari et al., 2003). Efficient factories can recover about 85% of the sucrose in the cane. Depending on the sucrose content of the cane and its recovery, 8%–15% of the millable cane harvested is recovered as raw (unrefined) sucrose (Clements, 1980; Jones, 1985).

The time of harvest is an important consideration in commercial sugarcane production because sugarcane harvested prior to complete ripening will not have reached its peak sucrose content and sugar yields will be reduced (Gilbert et al., 2006). Sugarcane grown in subtropical areas with cool winter seasons is normally harvested over a period of several months as daylengths decrease and temperatures cool. These conditions, along with the imposition of moderate drought stress by reduction in irrigation and/or application of chemical ripeners, cause stalk elongation to decrease relatively more than the decrease in photosynthesis. The result is increasing sucrose concentrations in stalk tissues and increased sucrose recovery in the mill. For example, in the Florida sugarcane industry, harvest occurs over a 5 month period (October–mid March) (Gilbert et al., 2006).

Most of the world's sugarcane is harvested at an age of approximately 1 year. In subtropical areas, the plant crop is often planted in the spring or summer season and is harvested 15–18 months later. Several 1 year ratoon crops usually follow the plant crop. Tillage and planting operations (including sett production for vegetative propagation) make the plant crop more costly to produce than ratoon crops (Salassi and Giesler, 1995). But ratoon crop yields are typically less than plant crop yields. For example, in Louisiana, yields typically decrease with each subsequent ratoon (Shrivastava et al., 1992; Johnson et al., 1993). The reasons for this decline are complex, but primarily relate to diseases, insects, weed competition, management practices, and winter kill (Shrivastava et al., 1992). Additionally, genotypes can vary substantially in their ability to produce good ratoon crop yields (Chapman, 1988; Chapman et al., 1992). Ratooning ability can be enhanced by indirect selection for disease and insect resistance, a well as by the direct selection of genotypes with high ratoon crop yields. Traits such as high stalk number, bud viability, vigorous root formation, high biomass accumulation, and high light-use efficiency have been suggested as being indicative of

better ratooning cultivars (Sundara, 1989). The importance of maintaining stalk weight in older crops has also been noted (Chapman, 1988; Chapman et al., 1992).

Ratooning ability can be defined in either absolute or relative terms. In absolute terms, a good ratooning cultivar is one that produces high ratoon crop yields or several profitable ratoon crops. In relative terms, a good ratooning cultivar is one whose ratoon crop yields are a high percentage of its plant cane yields. Cultivars with high plant cane yields commonly produce high and numerous ratoon crop yields, but exceptions exist (Chapman, 1988; Sundara, 1989; Milligan et al., 1996).

One-year sugarcane is bred and managed to avoid lodging, greatly facilitating both mechanical and manual harvesting. However, in the Hawaiian industry, stems of 2 year crops can reach a length of 10 m or more by growing upward, lodging, and then turning upward again. At harvest, the 2 year crop consists of a mat of tangled stems that have lodged several times. This requires very different mechanical harvesting systems and selection of varieties adapted to a 2 year growth cycle (Clements, 1980).

15.5 SUMMARY

Sugarcane is the world's most important sugar as well as ethanol crop. It probably was domesticated in New Guinea in prehistoric times, and it is widely grown in tropical and subtropical environments from 36°N to 31°S latitude. Sugarcane's greatest asset is its ability to produce sugar efficiently and in great quantity per unit land area. Sugarcane cultivation can substantially contribute to the supply of renewable energy, but improved crop husbandry and precision farming principles are needed to sustain and improve the resource base on which production depends. As a result of its C_4 photosynthetic pathway, maximum crop growth rates are over 40 g m^{-2} day^{-1}, and total dry matter production in many areas exceeds 40 metric tons ha^{-1} $year^{-1}$. Maximum fresh cane yields are over 200 Mg ha^{-1} $year^{-1}$, with sucrose concentrations of 7%–13%. Commercial yields are usually less than half the maximum yields.

Most sugarcane is grown as a 1 year crop, and several ratoon crops are normally produced. The ideal environment for a 1 year crop would include at least 4–5 months with high solar radiation and mean daytime temperatures of 30°C–35°C to stimulate growth. Prior to harvest, 1.5–2 months of cooler temperatures help increase sucrose concentrations. Little growth occurs when mean air temperatures are below 20°C.

Sugarcane can be grown in a wide variety of soils and tolerates soil pH from 4 to 9, but the optimum pH range is 5.8–7.2. Cane and sugar yields are sensitive to drought, poor soil aeration, salinity, and nutrient deficiencies and toxicities. Because of its high value, sugarcane producers usually attempt to minimize stresses by the application of irrigation, fertilizers, soil amendments, and pesticides. However, moderate drought and nitrogen stresses are often imposed for 1–2 months prior to harvest to increase cane sucrose concentrations.

Because of its long duration, high growth rates, and harvest of all millable cane (and sometimes tops and leaves), large amounts of nutrients are removed from the field. One metric ton of fresh millable cane contains about 1.6 kg N, 1 kg P, and 3.4 kg K. Since yields of 50–100 tons millable cane are common, fertilization is required to achieve adequate yields and maintain soil fertility. Both soil and plant analyses are used to detect and correct nutrient deficiencies and toxicities. The yield of sugarcane has increased over the last 50 years on a world basis, with some countries obtaining much greater increases than others.

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16 Cassava and Potato

16.1 INTRODUCTION

Cassava (*Manihot esculenta* Crantz) and potato (*Solanum tuberosum* L.) are the most important root/tuber crops used for human food. These two crops are also used as livestock feed and as a raw material source for the manufacture of alcohol, flour, and starch. Cassava is mostly grown and consumed in the tropics, while potatoes are grown commercially in most countries of the world. The climatic and soil requirements, growth and development, major physiological parameters related to the yield and mineral nutrition of these two crops are discussed in this chapter. A synthesis of the information and selected references in this chapter will help readers understand the production, physiology, and mineral requirements of these two crops.

16.2 CASSAVA

Cassava is a food crop of great importance in developing countries (Henry and Hershey, 2002; Halsey et al., 2008; Carretero et al., 2009). According to the United Nations Food and Agriculture Organization, cassava is an essential part of the diet of more than half a billion people (FAO, 2000). The starchy root of cassava is most frequently grown as a food source by small farmers in developing countries (Hillocks, 2002; Onwueme, 2002; Halsey et al., 2008). The major portion of the economic product, the root, is consumed as human food after varying degrees of processing. It is also used for animal and industrial starch and is becoming an important source of cash income to a large number of small farmers in Africa, Asia, and South America (Kawano, 2003). The genus *Manihot* originates in South and Central America, where there are two centers of diversity, in Brazil and Mexico (Beeching et al., 1993). Allen (2002) reported that cassava is a perennial crop native to tropical America, with its center of origin in northeastern and central Brazil. Contrary to the view that cassava is only known in cultivation, wild populations of the species grow over much of the American neotropics, in Brazil, Bolivia, Peru, Venezuela, Guyana, and Surinam (Allen, 1994). Three subspecies are recognized. *Manihot esculenta* subspecies *esculenta* is the domesticate and includes all cultivars known in cultivation. The wild *M. esculenta* subspecies *peruviana* occurs in eastern Peru and western Brazil. The wild *M. esculenta* subspecies *flabellifolia* shows a wider distribution and ranges from the central Brazilian state of Goiás northward to Venezuelan Amazonia. The large area of distribution of the two wild subspecies makes it difficult to assign a place of initial domestication (Allen, 1994). From its area of domestication in South America, it was taken to Africa by Portuguese as early as 1558 and spread to Asia in the seventeenth century (Cock, 1984). The maximum production of cassava is in Africa, followed by Asia and South America. In 2007, the leading cassava-producing countries and their production (in million metric tons) were Nigeria (34), Thailand (27), Brazil (27), Indonesia (20), Congo (15), Ghana (10), Angola (9), India (8), Vietnam (8), and Tanzania (7) (FAO, 2009).

Cassava is a perennial shrub belonging to the family Euphorbiaceae and subfamily Crotonoideae. Cassava also called mandioca (Brazil, Paraguay, and Argentina), yuca (other Spanish countries), tapioca (Asia), manioc (French-speaking Africa), and more than a half dozen vernacular names in other African countries (Kawano et al., 1978b). Although it is one of the world's most important food staples, cassava is known in North America and Europe almost solely as tapioca, an occasional dessert, and as an ethnic food (Janick et al., 1974).

A monoecious species, the female flowers normally open 10–14 days before the male flowers on the same branch, increasing the probability of cross fertilization. But self fertilization can occur because male and female flowers on different branches or on different plants of the same genotype open simultaneously (Jennings and Iglesias, 2002). The plant is easily propagated vegetatively, and in commercial production, cassava is planted by stem cuttings (Kawano et al., 1978a).

The average world yield is about 8.7 Mg of fresh root ha^{-1}, which is far below the potential yield of 80 Mg ha^{-1} produced under experimental conditions (Howeler, 1985). This large gap between potential and actual productivity is due to the fact that the crop is largely produced by subsistence farmers with low technology. Cassava's high yield potential has been attributed to several factors, including high crop dry weight in relation to foliage development, great leaf area duration, canopy architecture, and a high ratio of storage root dry weight to total dry weight, the harvest index (Jose and Mayobre, 1982).

16.2.1 Climate and Soil Requirements

Although cassava is, by origin, a tropical crop, it is successfully grown in latitudes up to 25°S in South America, southern Africa, and in some trial commercial plantings in high latitudes of Australia (Harris, 1978a). Cock and Rosas (1975) and Cock (1983) have suggested that cassava can be produced successfully between latitudes 30°N and 30°S at elevations up to 2300 m. But cassava is very sensitive to frost and in areas with marked seasonal temperature changes, cassava is grown only when the annual mean temperature is greater than 20°C (Cock, 1983). Ellis et al. (1982) found that few seeds germinate unless the temperature exceeds 30°C; the best rates occur at 30°C–35°C. Cassava is grown in areas with as little as 750 mm average rainfall per year since the crop has an extremely conservative pattern of water use. Reduced leaf area and stomatal closure markedly reduce crop growth rates during periods of drought stress (Connor et al., 1981). Carretero et al. (2009) reported that the infection of cassava roots by arbuscular mycorrhizal (AM) fungi improves drought adaptation.

Cassava is efficient in carbohydrate production, adapted to a wide range of tropical and subtropical environments, and tolerant of drought and acid soils (Kawano, 2003). It can grow on infertile soils varying in texture from light to heavy with pH from 3.5 to 7.8, but it will not tolerate poor drainage or high salinity. Howeler (2002) reported that cassava is a "scavenger" crop, efficient in nutrient capture and removal, and can grow on depleted and degraded soils where other crops fail. In Africa, cassava is used in cropping systems to regenerate soil fertility (Saidou et al., 2004; Adjei-Nsiah et al., 2007). The highest yields occur on well-drained, medium-to-heavy texture, fertile soils with a pH of about 5.5–7 (Howeler, 1981). Abruna et al. (1982) found that cassava is highly tolerant to soil acidity. Yields of cassava grown on a Corozal clay (Aquic Tropudults) decreased only when soil pH dropped below 4.3 and exchangeable Al increased above 60% saturation. Cassava is more susceptible than most food crops to soil salinity and alkalinity, but large varietal differences in tolerance exist. Yields are markedly reduced when the Na saturation is above 2%–5% and the electrical conductivity is above 0.5–0.7 dS m^{-1} (Cock and Howeler, 1978).

16.2.2 Growth and Development

Cassava has no critical growth periods, such as anthesis in the grain crops, when stress may cause major crop failure or even total crop loss. This is because the growth and development of the economically useful plant parts (storage roots) occurs at the same time as growth of the leaf and stem structures required to supply them with energy (El-Sharkawy, 2003; Lenis et al., 2006). The growth and development of the cassava plant is dominated by the crop's ability to maintain an adequate leaf area index (LAI) over a long period of time while allocating much of its dry matter production to production of storage roots (Cock and El-Sharkawy, 1988).

The basic constituents of the cassava plant are (1) nodal units that consist of a leaf blade, petiole, and internode, and (2) thickened roots that form mainly at the base of the stem cutting that is used as planting material. The dry weight of stem internodes varies among varieties and averages from 0.5 to 3.0 g per internode for a mature plant. Leaves have an area-to-weight ratio of about 135 cm^2 g^{-1}.

The plant generally shows strong apical dominance and does not generally produce leaves from the axillary buds (Cock et al., 1979).

Cassava can be propagated with either true seed or stem cuttings. Planting cuttings is the normal practice for commercial production, while planting seed is practiced in breeding programs. Stem cuttings, preferably taken from the middle of the stems, are normally about 20 cm long. The growth duration of the crop depends on environmental conditions. The period from planting to harvest is about 9–12 months in hot regions and up to 2 years in cooler or drier regions (Cock, 1984).

16.2.2.1 Roots

Roots are the main storage organs in cassava. Secondary thickening results in tuber development as swellings on adventitious roots, a short distance from the stem. The tubers are cylindrical or tapering, 15–100 cm long, 3–15 cm across, and occasionally branched (Purseglove, 1987). Keating et al. (1982) reported that the final number of storage roots was generally reached within 90–135 days after planting and ranged from 10 to 14 storage roots per plant, independent of planting date and season. Campos and Sena (1974) studied the root system of cassava and found most roots concentrated in the top 30 cm, with some roots as far down as 140 cm; however, Connor et al. (1981) found roots at a depth of 250 cm. They also observed root characteristics and found that cassava has thicker roots than most species (0.37–0.67 mm diameter), but its rooting density is low (less than 1 km of roots m^{-2} land surface).

16.2.2.2 Tops

Cassava plants vary in height and branching habit. Each nodal unit consists of a node that subtends a leaf on an internode. The total number of nodes per plant depends on the number of nodes per shoot and the number of shoots, or apices, per plant (Cock, 1984). Cassava leaves are spirally arranged (phyllotaxis 2/5), and variable in size, color of stipules, petioles, midribs, and laminae, and in number, depth, shape, and width of lobes (Purseglove, 1987). Sangoi and Kruse (1993) measured plant height during the crop growth cycle on the highlands of Santa Catarina, Brazil. During the first 60 days of plant growth, plant height increase was slow (Figure 16.1). Maximum plant height increased rapidly from 60 to 180 days after planting, and maximum plant height was reached at about 210 days after sowing.

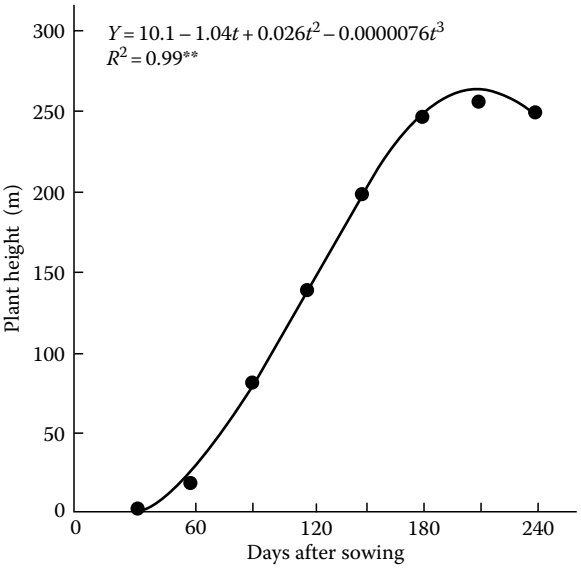

FIGURE 16.1 Cassava plant height during crop growth in a Cambisol of Brazil. (From Sangoi, L. and Kruse, N.D., *Pesq. Agropec. Bras. Brasilia,* 28, 1151, 1993.)

16.2.2.3 Leaf Area Index

LAI is an important growth parameter, which determines the photosynthetic capacity of a crop. It is affected by climatic factors, soil fertility levels, and cultural practices. LAI normally increases in the first 4–6 months after planting, reaches a maximum value, then declines during the latter part of the cropping season due to leaf abscission (Williams, 1972; CIAT, 1979). The maximum LAI values reported in the literature are between 6 and 8 (Enyi, 1972). According to Keating et al. (1982), substantial leaf abscission begins at LAI values on the order of 5–6.

Cock et al. (1987) reported that the photosynthesis of cassava indicates that it is intermediate between C_3 and C_4 pathways. In general, plants with C_4 pathway of photosynthesis produce more biomass per unit leaf area and also use water more efficiently. Cassava has the enzyme systems for C_4 photosynthesis, although they are not as active as in the case of corn, a C_4 species (Cock and El-Sharkawy, 1988). Furthermore, cassava does not possess the kranz leaf anatomy typical of the true C_4 plants (Cock and El-Sharkawy, 1988). Cassava reaches a maximum growth rate of 120–150 g m^{-2} per week at an LAI of about 4 under solar radiation of about 450 cal cm^{-2} day^{-1} (Cock, 1983).

The maximum crop growth rates of cassava within the tropics are of the order of 120 g dry matter m^{-2} $week^{-1}$ (Cock, 1984). Figure 16.2 illustrates the linear relationship between cassava LAI and the growth rate of leaves and stems. In contrast, the maximum root growth rate is achieved at an LAI of about 3–4. Total plant growth rate increased up to 4 LAI and then remained relatively constant. Similarly, Cock and El-Sharkawy (1988) reported that total crop growth rate increases up to an LAI of approximately 4–5, when over 95% of solar radiation is intercepted by the crop canopy.

16.2.2.4 Dry Matter

Irizarry and Rivera (1983) found that on a Puerto Rican Ultisol dry matter in stems, roots, and the whole plant increased steadily with plant age (Figure 16.3). Leaf dry matter decreased gradually 5–8 months after planting as full ground cover was achieved and older leaves began to senesce. Total plant dry matter 10 months after planting was 23 Mg ha^{-1}, and dry matter in edible fresh roots was about 11 Mg ha^{-1}. In a similar study in Colombia, Howeler and Cadavid (1983) found

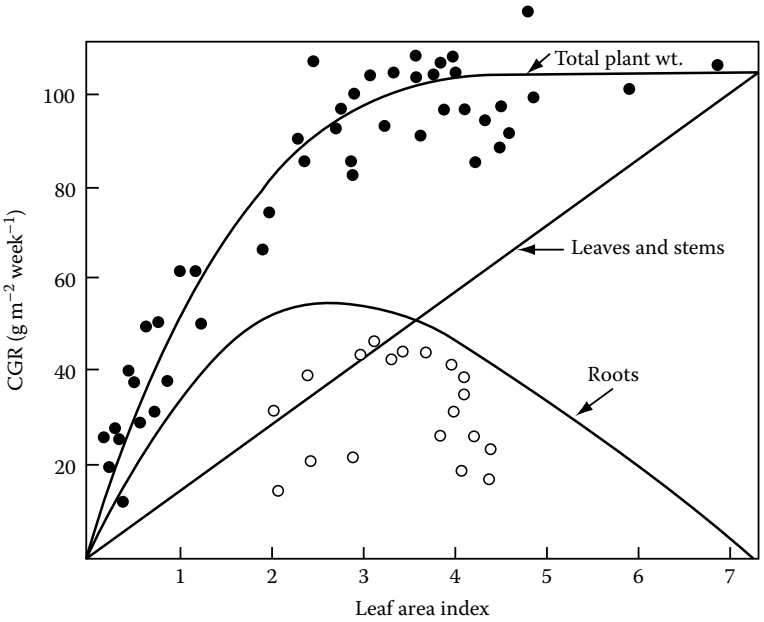

FIGURE 16.2 Leaf area index and crop growth rate. (From Cock, J.H., Cassava, in *Potential Productivity of Field Crops under Different Environments,* IRRI (ed.), IRRI, Los Banos, Philippines, 341–359, 1983.)

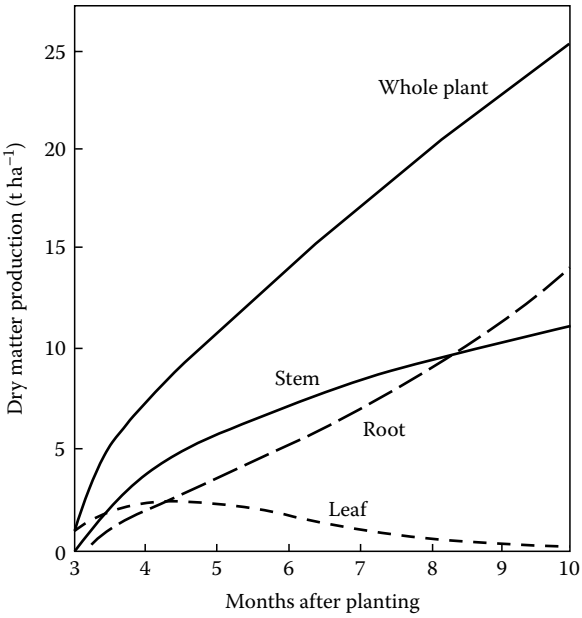

FIGURE 16.3 Dry matter accumulation among different plant parts of Cassava. (From Irizarry, H. and Rivera, E., *J. Agric. Univ. Puerto Rico*, 67, 213, 1983.)

that cassava dry matter accumulation was slow during the first 2 months, increased rapidly during the next 4 months, and slowed down during the final 6 months as dry matter production was partly offset by leaf fall. At harvest (12 months), dry matter accumulation was greatest in storage roots, followed by stems, leaf blades, and petioles. Sangoi and Kruse (1993) determined the fresh weight of storage roots in a Brazilian Cambisol during the crop growth cycle. Storage roots began to grow about 80 days after planting and reached their maximum weight of 15 Mg ha^{-1} at about 210 days (Figure 16.4).

16.2.2.5 Harvest Index

Harvest index (HI) is the fraction of total dry matter in the economically useful plant parts. In cereals, it is the ratio of grain yield to total aboveground dry weight. In cassava, storage roots are the economic yield component, and HI is the ratio of storage root to total crop dry matter. Cock (1976) obtained HI values after 1 year ranging from less than 0.30 to 0.57 for a number of clones at a plant population of 20,000 plants ha^{-1}. In one trial with variety M col.22, HI values of more than 0.7 were obtained, but HI decreased as population increased above 12,000 plants ha^{-1} (Cock et al., 1977). HI can be used as one of the selection criteria for higher yield potential in cassava cultivars (Kawano, 1978). According to Iglesias et al. (1994), HI of 0.5–0.6 is the optimum level because at higher values of HI, root production decreases due to reduced leaf area, light interception, and photosynthesis.

16.2.3 Soil Nutrient Requirements

Cassava is considered to be tolerant to low soil fertility and grows well on acid soils where other crops cannot be grown satisfactorily (Howeler, 1981). Although this crop has been traditionally grown without the use of fertilizers, it is now well established that the cassava responds well to fertilization, and in order to obtain high yield, adequate nutrients must be supplied (Howeler, 1981; Howeler and Cadavid, 1983). Howeler (1981) summarized the response to fertilization and liming in three important tropical soil orders (Oxisols, Ultisols, and Inceptisols). Phosphorus is generally the element most limiting to yield. Cassava extracts large amounts of K from soil and may cause

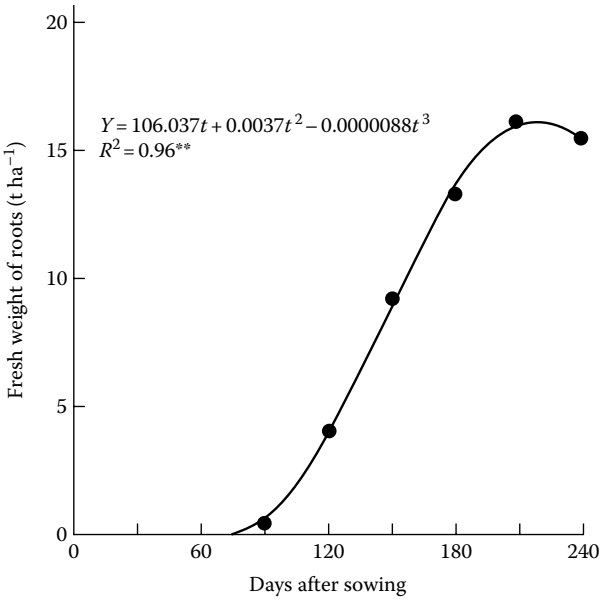

FIGURE 16.4 Fresh weight of roots during crop growth cycle. (From Sangoi, L. and Kruse, N.D., *Pesq. Agropec. Bras. Brasilia,* 28, 1151, 1993.)

depletion of this element if grown continuously without adequate K fertilization. Compared to other crops, cassava has a low requirement for N, and high N application may lead to excessive top growth, a reduction in starch synthesis, and poor root thickening (Howeler, 1981). Cassava is tolerant of acid soils and has an optimum pH of 5.5–7.5. The crop often responds to a low rate of liming, but overliming may induce micronutrient deficiencies. The critical extractable soil nutrient levels reported by Howeler (1981), based on results from several studies, are 7–9 mg kg^{-1} P, 0.06–0.15 cmol kg^{-1} K, 0.25 cmol kg^{-1} Ca, 1 mg kg^{-1} Zn, 5–9 mg kg^{-1} Mn, and 8 mg kg^{-1} S.

In the following sections, nutrient concentrations and the quantity of nutrients removed by cassava are discussed. This information may form the basis for an understanding of the nutritional requirements of this important root crop.

16.2.3.1 Plant Nutrient Concentrations

Nutrient concentrations in plants vary with the plant part analyzed, stage of plant growth, soil fertility, climatic conditions, and management practices (Howeler, 1981; Howeler and Cadavid, 1983). Nutrient sufficiency levels in cassava tissue reported in the literature are summarized in Table 16.1. In general, it may be concluded that a fertilizer response is not likely when the uppermost mature leaf blades contain 50–60 g kg^{-1} N, 3–5 g kg^{-1} P, 12–20 g kg^{-1} K, 6–15 g kg^{-1} Ca, 2.5–5 g kg^{-1} Mg, and 3–4 g kg^{-1} S. Similarly, a fertilizer response is not expected when the Cu concentration in leaf tissue is 7–15 mg kg^{-1}, Zn 40–100 mg kg^{-1}, Mn 50–250 mg kg^{-1}, Fe 60–200 mg kg^{-1}, and B 15–20 mg kg^{-1}. Irizarry and Rivera (1983), working in a Puerto Rican Ultisol, reported that 6 months after planting, optimum leaf concentrations were approximately 43, 1.2, 18, 14, and 4 g kg^{-1} for N, P, K, Ca, and Mg, respectively.

16.2.3.2 Nutrient Accumulation

Plant nutrient accumulation (concentration × dry matter) patterns can provide useful information about the fertilizer requirements of a crop. Howeler and Cadavid (1983) studied nutrient accumulation in different plant parts of cassava in Colombia throughout the growth of the crop. Most nutrients accumulated initially in leaves and stems, but were translocated to roots in the later part of the growth cycle. By the time of harvest, only Ca, Mg, and Mn accumulated more in stems than roots. Nutrient removal at the 12-month growth period was in the order of N > K > Ca > P > Mg > S > Fe > Mn > Zn > Cu > B.

TABLE 16.1
Nutrient Sufficiency Levels in Cassava Plant

Nutrient	Growth Stage	Plant Part	Sufficiency Level ($g\ kg^{-1}$)
N	Vegetative	UMB[a]	50–60
P	Vegetative	UMB	3–5
K	100 DAS[a]	UMB	12–20
	200 DAS	UMB	6–10
	580 DAS	UMB	5–10
Ca	Vegetative	UMB	6–15
Mg	Vegetative	UMB	2.5–5
S	Vegetative	UMB	3–4
			$mg\ kg^{-1}$
Cu	Vegetative	UMB	7–15
Zn	Vegetative	UMB	40–100
Mn	Vegetative	UMB	50–250
Fe	Vegetative	UMB	60–200
B	Vegetative	UMB	15–20

Source: Compiled from Reuter, D.W., Temperate and subtropical crops, in *Plant Analysis: An Interpretation Manual*, Reuter, D.J. and Robinson, J.B. (eds.), Inkata Press, Melbourne, Australia, 38–99, 1986.

[a] DAS, days after sowing; UMB, uppermost mature leaf blade.

Irizarry and Rivera (1983) reported that in an Ultisol of Puerto Rico, 10 months after planting, cassava had accumulated 204 kg N ha^{-1}, 13 kg P ha^{-1}, 222 kg K ha^{-1}, 86 kg Ca ha^{-1}, and 33 kg Mg ha^{-1}, with a total dry matter production of about 23 t ha^{-1} of leaves, stems, and roots. Howeler (1981) calculated nutrient removal by cassava roots based on various studies in the literature and concluded that, on the average, each ton of cassava roots removed 2.3 kg N, 0.5 kg P, 4.1 kg K, 0.6 kg Ca, and 0.3 kg Mg.

16.3 POTATO

The potato (*Solanum tuberosum* L.) belongs to the family Solanaceae and is a herbaceous annual plant grown for edible tubers. Actually, tubers are underground stems and are high in carbohydrates, exceedingly low in sodium and relatively rich in potassium and vitamin C, making it a good dietary complement to meats and pulses (Ulrich, 1993). In 2007, the value of world potato (*Solanum tuberosum* L.) production ($35 billion) ranked behind paddy rice ($131 billion), wheat ($73 billion), soybean ($45 billion), corn ($38 billion), and cotton lint ($38 billion). But potato production value was greater than sugarcane ($32 billion), peanuts in the shell ($17 billion), and cassava ($14 billion). In 2007, in the United States, potato production ($20 billion) was sixth behind corn ($331 billion), soybean ($73 billion), wheat ($56 billion), sugar beet ($32 billion), and sugarcane ($28 billion). But among field crops in the United States it was fifth in terms of value ($2.8 billion) behind corn ($20.9 billion), soybean ($14.9 billion), wheat ($7.7 billion), and cotton lint ($6.2 billion) (FAO, 2009).

The origin of potato is believed to be the Andean region of Peru and Bolivia, and it has become a major dietary staple in almost all temperate countries (Robson et al., 2002). Although many crops were brought to Europe by Columbus and others soon after the discovery of the New World in 1492, the potato arrived much later. This is because it is a cool-temperate crop of the high Andes of

South America, and it was not discovered by the Spaniards until 1532. Potatoes were not recorded in the literature until 1537 in what is now Colombia and did not appear in published work until 1552 (Hawkes and Ortega, 1993). The potato was taken to Europe by the Spanish around 1570 and introduced into England in 1586. From Europe, it spread to Africa and Asia. In the United States, potatoes are said to have been introduced in 1621, presumably via Bermuda, but it was not extensively planted in the United States until about 1700. It is now planted in almost all countries.

In 2007, the world's 10 potato producing countries (in million metric tons) were China (65), Russian Federation (37), India (22), United States (20), Ukraine (19), Poland (12), Germany (12), France (7), Netherlands (7), and Iran (5) (FAO, 2009). It is estimated that 79% of countries in the world grow potato (Donnelly et al., 2007). In North America, the dry matter production of potatoes per unit of land area exceeds that of wheat, barley, and corn by factors of 3.04, 2.68, and 1.12, respectively. Potato protein yield per unit of land area exceeds that of wheat, rice, and corn by factors of 2.02, 1.33, and 1.20, respectively (Hooker, 1986). Besides being used for human consumption, potatoes are used as a feed for animals and for starch, spirits, and industrial alcohol. Potato tubers contain 70%–80% water, 8%–28% starch, and 1%–4% protein, with traces of minerals and other food elements. The nutritive value of potatoes has been discussed in detail by Gray and Hughes (1978).

16.3.1 Climate and Soil Requirements

The potato is classified as a cool-season crop, and it is best grown at places and in periods where average daily temperatures are above 5°C and below 21°C (Vos and Haverkort, 2007). It is normally grown in the tropics at elevations of approximately 2000 m or higher. The highest average yields are obtained in countries where day length is 13–17 h during the growing season, average temperatures around 15°C–18°C prevail, and rainfall or irrigation provides ample water (Haeder and Beringer, 1983). The thermal optimum for growth varies from 16°C to 28°C depending on the variety, age, and plant part considered (Burton, 1972; Marinus and Bodlaender, 1975; Benoit et al., 1986; Fleisher et al., 2006a,b). Optimum temperature for leaf photosynthetic rate ranges from 20°C to 24°C (Prange et al., 1990; Thornton et al., 1996). Benoit et al. (1983) have reported that leaf expansion has an optimum temperature of about 25°C, stem elongation has an optimum temperature of 31°C (at rhizome initiation when plants were 20 cm tall), and 27°C is optimum for early tuber bulking. Vegetative growth is favored by temperatures at the lower end of the range (Haun, 1975; Marinus and Bodlaender, 1975). Decreased plant growth occurs above and below the optimum temperatures, probably due to the dynamic balance between photosynthesis and respiration (Lahav and Trochoulias, 1982; Gent and Enoch, 1983). Timlin et al. (2006) reported that the optimum temperature for canopy photosynthesis is 24°C early in the growth period and shifts to lower temperatures as the plants age. Optimum temperatures for the growth and development of potato plants are given in Table 16.2.

Potatoes are quite sensitive to water stress, and an adequate water supply is required from tuber initiation until near maturity for high yields and good quality (Van Loom, 1981; Hang and Miller, 1986). The tuber bulking stage is more sensitive to drought stress than other growth stages (Hang and Miller, 1986). According to Harris (1978b), the potato crop is very sensitive to soil water deficits, and for near-maximum yields, this deficit should not be allowed to exceed approximately 50% of the available water within the root zone of the crop. Water requirements for the potato may be assessed by measuring the soil water tension range at which water is readily available for plant growth. Optimal soil water potential for the potato has been reported to range between −20 and −60 kPa (Van Loom, 1981). Allowing the soil water potential to become drier than −60 kPa may reduce production and translocation of assimilates (Manrique, 1992); however, extended periods with soil water potential greater than −20 kPa may reduce tuber yields due to poor soil aeration. The permanent wilting point of potato crops is typically −0.6 MPa in young crops, falling to −1.0 MPa in older crops, both of which are higher than the commonly accepted value of −1.6 MPa (Vos and Haverkort, 2007). These figures imply that potato has a weaker capacity to dry out the soil than crops that wilt at −1.6 MPa or lower. Vos and Haverkort (2007) also reported that potato is a crop

TABLE 16.2
Optimum Temperature for Growth and Development of Potato

Growth and Development	Optimum Temperature (°C)
Sprouting	16–20
Sprout growth	20–25
Emergence	20–25
Early shoot growth	24
Leaf area development	20–25
Stem elongation	>25
Shoot growth	32
Photosynthesis leaf	24
Dry matter production	20
Tuber initiation	22
Dry matter partitioning to tubers	20
Tuber yield	20–24

Source: Adapted from Struik, P.C., Responses of potato plant to temperature, in *Potato Biology and Biotechnology: Advances and Perspectives,* Vreugdenhil, D. (ed.), Elsevier, New York, 366–393, 2007b.

that uses water relatively efficiently. Its high HI of about 0.75, compared with approximately 0.50 for cereals, contributes to this property.

Potato can be grown on a wide range of soils. It is well suited to acidic soils, and its optimum pH range is from 5.2 to 6.5 (McLean and Brown, 1984). The limited response of potato to liming suggests that soil acidity and Al toxicity are not serious constraints to potato growth in all but the most acid soils. The percentage Al saturation is a useful index of soil acidity constraints and lime requirements for different crops. Potato suffers no yield decline at an Al saturation of less than 20% (Manrique, 1992). Potatoes also grow well at a higher soil pH, but common scab (*Streptomyces scabies*) disease may become a problem. Common scab is sensitive to soil pH and has an optimal pH range of 5.4–7.4 for activity and infection of potato tubers (Keinath and Loria, 1989). If it is not practical to maintain a low pH, scab-resistant cultivars must be grown (Ewing, 1997). Sandy, well-drained loams, and soils high in organic content, are generally best for potato growing, and the most attractive tuber shape and skin appearance are achieved with light, sandy soils, or with muck soils. The potato plant is considered moderately tolerant to soil salinity and the salinity threshold for yield decline is reported to be about 1.7 dS m^{-1} (Maas and Hoffman, 1977).

Potato tuber growth and quality are also reduced by soil compaction. Tuber yield and quality in both compacted and normal soils were best when the soil moisture potential was near −0.5 MPa. In moister soils (−0.2 MPa), enlarged lenticels were more prevalent, and in drier (−0.7 MPa) and severely compacted soils the yield and quantity of tubers diminished. Neither changes in fertilizer nor irrigation practices alleviated the adverse effects of soil compaction on potato yield or quality, but without the proper control of the soil moisture in compacted soils, tuber yield and quality were more severely affected (Timm and Flocker, 1966).

16.3.2 Growth and Development

The potato is commercially propagated vegetatively (using seed tubers) and true seeds are used only in breeding programs. The commercial potato plant usually contains one or more lateral shoots, each arising from a bud on the seed tuber, and the roots are adventitious (Hooker, 1986).

On these shoots, the stems, foliage, stolons, roots, inflorescence, and the next generation of tubers are formed (Struik, 2007a). The rhizomes of the potato plant are usually called stolons. The tubers are swollen parts of the subterranean rhizomes or stolons and are globose to ellipsoid in shape (Struik, 2007a). The life cycle of the potato plant can be described in terms of the period until induction of flowering, the time to tuber initiation, the time to onset of rapid tuber bulking, the time to cessation of shoot growth, and the time to onset of senescence. These growth phases are closely associated, in terms of both crop physiology and time, but the time lapse between the different phases depends on the genotype, the environment and the genotype by environment interaction (Struik, 2007b). Potato cultivars are often characterized as determinate or indeterminate. Determinate types tend to have a short life cycle and short stature because they do not produce many orders of stem branches. Indeterminate types, however, tend to grow tall, produce more orders of branches, and have a long growth cycle. The yield potential of indeterminate types is greater than that of determinate types, but they need a much longer growing season to realize their potential (Struik, 2007a). The potato crop is normally harvested from 3 to 4 months after planting. Figure 16.5 summarizes the development of the potato plant through the different growth stages.

16.3.2.1 Roots

Potato plants grown from true seeds have a primary tap root system, whereas commercial potato plants grown from tubers have only adventitious roots. But in both cases, a much-branched fibrous root system is formed (Cutter, 1978). Harris (1978c) summarized the work of various investigators and came to the conclusion that potato roots are essentially restricted to the 0–30 cm soil depth, and root system density decreases rapidly below this depth. Struik (2007b) reported that potato root system is rather weak, and therefore, water- and nutrient-use efficiencies in potato are low, and the crop is very sensitive to drought and poor soil structure. Seed tubers should be planted sufficiently deep enough to permit adequate root and stolon formation (Hooker, 1986).

16.3.2.2 Tops

The potato is an herbaceous, branched annual, 0.3–1 m in height, with swollen stem tubers (Purseglove, 1987). The vegetative stems (or branches) of the potato plant are usually quite thick and erect and, in indeterminate cultivars, are greatly branched. Stems range from 30 to 60 cm in length. Leaves are compound with terminal leaflets, two to four pairs of oblong, pointed leaflets and two or more smaller leaflets at the base. Though cultivars are described as determinate and indeterminate based on their growth habit, the species is botanically determinate because the flowers are borne in terminal rather than axillary cymes (Chapman and Carter, 1976).

16.3.2.3 Tubers

The tubers, which are the harvested portion of the potato plant, are modified, underground stems with greatly extended internodes. The tuber is formed at the tip of the stolon (rhizome) as a lateral proliferation of storage tissue resulting from rapid cell division and an approximately 64-fold increase in cell volume (Hooker, 1986). Tuber composition varies with the cultivar and growing conditions. But on average, fresh tuber constituents are water 63%–87%, carbohydrates 13%–30% (including a fiber content of 0.17%–3.48%), protein 0.7%–4.6%, fat 0.02%–0.96%, and ash 0.44%–1.9%. Additional constituents include sugars, nonstarchy polysaccharides, enzymes, ascorbic acid and other vitamins, phenolic substances, and nucleic acids (Hooker, 1986). The rate of tuber growth (the rate of bulking) is exponential for the first 2–3 weeks, but then becomes almost linear (Moorby and Milthorpe, 1973). Moorby (1968) reported a maximum tuber growth rate of 25 g m^{-2} day^{-1} and 60 tubers m^{-2}.

16.3.2.4 Dry Matter

The dry matter production of potatoes is commonly divided into three components: roots, tops, and tubers. Actually, tubers are the principal organ, which accumulates a major part of the total

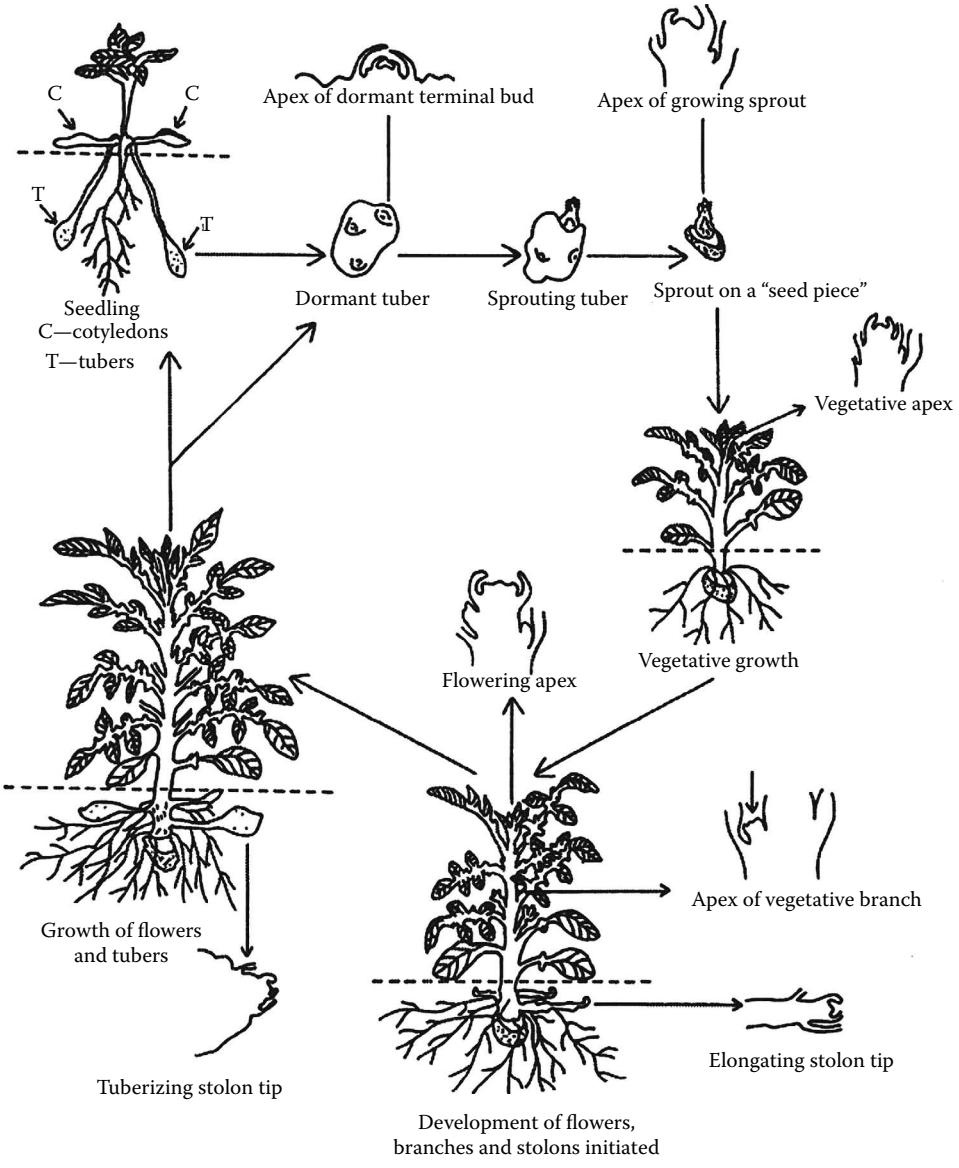

FIGURE 16.5 Diagrammatic representation of the development of a potato plant. Plantlets from seeds may form tuberizing stolons in the axils of cotyledons. Dormant tubers, as stored in the cold (6°C–7°C) after harvest, include several internodes with buds in the axils of scale leaves. Severed "seed pieces" produce sprouts from buds, and these give rise clonally to plants that develop first vegetatively then reproductively, as they form both sexual (i.e., flowers bearing seeds) and asexual (i.e., stolons and tubers bearing buds) reproductive organs. Throughout this cycle, it is the shoot apices that constitute the main seat of the developmental events. (Reproduced from Steward, F.C. et al., *Ann. Bot.*, 48, 1, 1981. With permission.)

dry matter production. Figure 16.6 shows the distribution of dry matter in roots, tops, and tubers of potatoes at different growth stages. Stage I, vegetative growth, is the period from emergence up to 30 days after emergence when tuberization is initiated (Kleinkopf et al., 1979). Stage II, in which early tuber bulking starts, covers 10–14 days following the vegetative stage when tubers form rhizome tips and there is some floral initiation. Dry matter production in growth stages I and II is very small. Most dry matter accumulation occurs in growth stage III, starting about 50 days after emergence and continuing until 100 days or more (Lorenz et al., 1954). During growth Stage III,

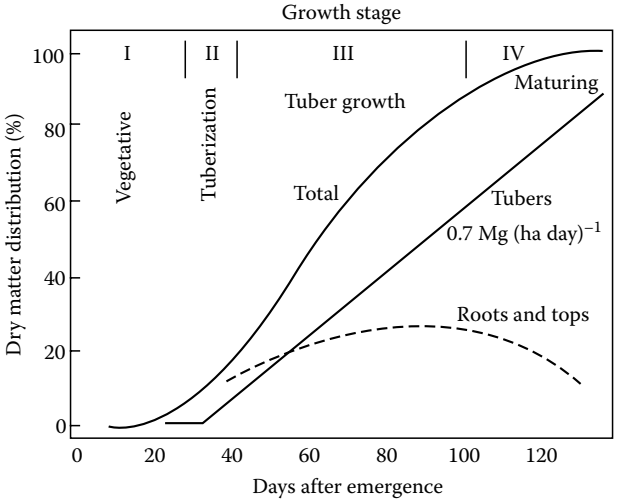

FIGURE 16.6 Dry matter distribution during four growth stages of russet Burbank potatoes. (From Kleinkopf, G.E. et al., Nitrogen effects and russet Burbank potato growth, in *Proceedings of the 30th Annual Northwest Fertilizer Conference*, Northwest Plant Food Association, Portland, OR, 143–150, 1979.)

after floral initiation, photosynthate and minerals are rapidly translocated into the tubers (Haeder et al., 1973). Growth Stage IV, which is designated as maturing, is characterized by vine yellowing, leaf senescence, and slowed growth rate. This stage begins about 100 days after emergence and continues to the end of the growing season (Roberts and Dole, 1985). Figure 16.6 shows very clearly the dominant role of tubers as a sink for assimilate over the greater part of the growing season.

The most important factor that determines dry matter production is the photosynthetic efficiency of the crop, which varies with cultivar, environmental conditions, and LAI. Allen and Scott (2001) reported that typically, potato crops achieve an LAI of 5.0–6.0, and maximum light interception (>90%) is achieved at LAI of about 4.0. Generally, an LAI of 4–5 is sufficient for higher tuber yields (Haeder and Beringer, 1983). Early canopy development is needed for maximum light interception and photosynthesis (Allen and Scott, 2001), and yield loss is significant when canopies remain below a LAI of 4.0 (Ziems et al., 2006).

16.3.3 Nutrient and Cultural Requirements

About 95% of the potato biomass is constituted of the elements carbon, hydrogen, and oxygen that the plant absorbs through the assimilation of carbon dioxide and the water uptake. The rest of the biomass is composed of a range of elements that have to be absorbed from the soil solution, some of which are usually supplied with the application of inorganic fertilizers (Bucher and Kossmann, 2007). A fair assessment of the nutrient requirement of a crop is the crop nutrient response curve. If a given soil is deficient in a nutrient, crop response to the addition of the limiting nutrient is expected, provided other growth factors are not limiting. To determine the response curve, fertilizer trials are needed for each type of soil and agro-ecological region. Figure 16.7 shows potato yield response to N application rates. In this case, yield response to fertilizer N was significant and quadratic, and the highest yield was obtained with about 200 kg N ha^{-1}. Nyiraneza and Snapp (2007) reported that the application of both chemical fertilizer and poultry manure (179 kg N ha^{-1} fertilizer + 5.6 Mg ha^{-1} poultry manure) consistently increased tuber yield and N uptake efficiency by 20% more than the use of only chemical fertilizer (224 kg N ha^{-1} fertilizer). Moinuddin and Umar (2004) reported that application of K and S increased tuber yield as well as tuber quality.

However, the impacts of fertilizers and soil amendments may be complex, especially as they affect potato diseases. For example, potato disorders such as brown center, hollow heart, are thought

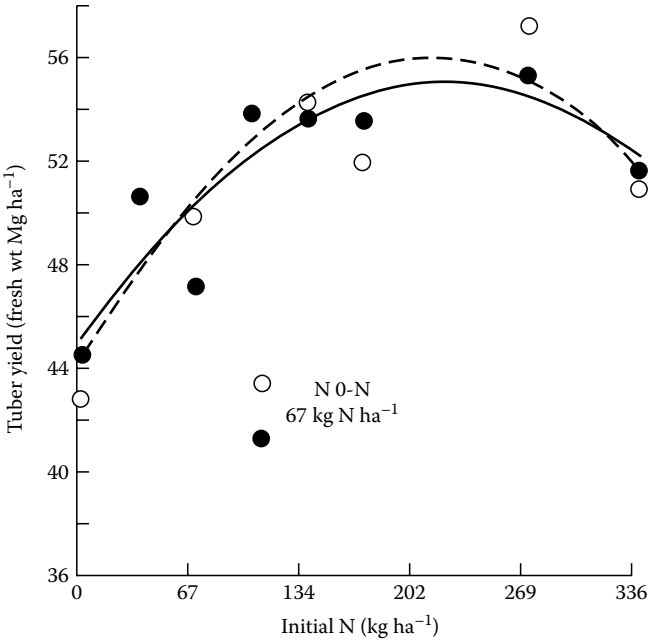

FIGURE 16.7 Potato yield response to initial application rates of NH_4NO_3-N for 2 years. Open circles and dashed lines represent treatments receiving additional application of 67 kg N ha^{-1} 21 days after tuber initiation. (From Westcott, M.P. et al., *Agron. J.*, 83, 844, 1991. With permission.)

to be related to tuber Ca level (Bangerth, 1979). In addition, it has long been known that potato scab can be controlled by the application of sulfur to reduce root zone pH (Oswald and Wright, 1950; Pratt, 1961), and Pavlista (2005) reported that potato yield was increased by S at 56 kg ha^{-1} applied at planting in the furrow, 11 days after emergence and at tuber initiation, probably because common scab (*Streptomyces scabies*) and black scurf (*Rhizoctonia solani*) were affected by application timing and fertilizer. However, common potato scab infection and damage respond in complex ways to soil acidity, cultivar resistance, soil moisture, soil type, organic amendments, and crop rotation. The control of common scab in New York is enhanced by use of resistant cultivars, scab-free seed and seed treatments, avoiding light-textured soils with high organic matter, maintenance of soil pH between 5.2 and 5.4, rotation of potato with alfalfa or grain crops, and avoiding moisture stress during the 2–6 weeks following tuber initiation (Loria, 1991).

Another example of nutrient–disease interaction involves potato late blight. Most authors agree that adequate P and K concentrations tend to reduce potato late blight (Awan and Struchtemeyer, 1957), whereas excessive nitrogen tends to increase the disease (Carnegie and Colhoun, 1983; Rotem and Sari, 1983; Phukan, 1993). In Mexico, nitrogen fertilization and incidence of potato late blight are two important agronomic factors which significantly influence potato production. Both deficient and excessive N fertilization can enhance late blight, with N deficiencies making plants more susceptible, and excessive N stimulating top growth and creating a canopy microclimate conducive to disease development (Rubio-Covarrubias et al., 2005).

16.3.3.1 Nutrient Concentrations

Considerable progress has been made in the use of plant analysis in determining the nutrient requirements of crop plants, including potatoes. Potato nutrient concentrations can provide guidelines for crop nutrient requirements, and detailed information about potato mineral requirements can be found in articles by Smith (1949), Harris (1978c), and Roberts and Dole (1985).

The fourth petiole of the most recently matured leaf from the growing tip is usually the plant part used for nutrient analysis in potatoes (Roberts and Dow, 1982). The evaluation of a plant's

TABLE 16.3
Adequate Nutrient Concentrations in Potato Plant

Nutrient	Growth Stage	Plant Part	Sufficiency Level
			g kg^{-1}
N	42 DAE[a]	UMB + P[a]	40–50
	Early flowering	UMB + P	55–65
	Tubers half grown	UMB + P	30–50
P	42 DAE	UMB + P	2–4
	Early flowering	UMB + P	3.5–5.5
	Tubers half grown	UMB + P	2–4
K	42 DAE	UMB + P	35–50
	Early flowering	UMB + P	45–65
	Tubers half grown	UMB + P	40–80
Ca	42 DAE	UMB + P	6–9
	Early flowering	UMB + P	10–20
	Tubers half grown	UMB + P	15–25
Mg	42 DAE	UMB + P	8–11
	Early flowering	UMB + P	3–5
	Tubers half grown	UMB + P	5–8
S	Early flowering	MSL	3–5
	Tubers half grown	PUMB[a]	1.9–3.6
			mg kg^{-1}
Fe	Tubers half grown	UMB + P	70–150
Mn	Tubers half grown	UMB + P	30–450
Zn	Tubers half grown	UMB + P	20–40
B	Tubers half grown	UMB + P	30–40
Mo	Early flowering	MSL	0.1–1.5

Source: Compiled from Piggott, T.J., Vegetable crops, in *Plant Analysis: An Interpretation Manual,* Reuter, D.J. and Robinson, J.B. (eds.), Inkata Press, Melbourne, Australia, 148–187, 1986.

[a] DAE, days after emergence; UMB + P, uppermost mature leaf blade + petiole; PUMB, petiole of uppermost mature leaf blade; MSL, midstem leaves.

nutritional status is based on a significant relationship between the nutrient in question and plant yields. This relationship is called a nutrient response curve and can be used to identify nutrient concentrations that are deficient, adequate, and excessive (Westermann and Kleinkopf, 1985). Based on this concept, the adequate levels of various nutrients in potato plant tissue are presented in Table 16.3.

16.3.3.2 Nutrient Accumulation

Information on nutrient accumulation by potato crops is helpful in developing fertilizer programs (Roberts and Dole, 1985). The quantity of nutrients removed in the harvested portion of the crop will depend on the yield and the concentration of the nutrients, and both can vary from place to place and year to year. Table 16.4 shows the amount of nutrients removed by the tops and tubers of potatoes. Nitrogen and potassium are removed in large quantities, both by tops and tubers. This means these two elements are most likely to be deficient in normal agricultural soils and must be supplied in adequate quantities to obtain higher yields.

TABLE 16.4
Nutrient Accumulation in Tops and Tubers for Russet Burbank Potatoes Yielding 79 t ha^{-1} in an Irrigated Field of Central Washington

	Nutrient Accumulation (kg ha^{-1})[a]		
Nutrient	**Tops**	**Tubers**	**Total**
N	140	282	422
P	7	40	47
K	200	320	520
Ca	60	12	72
Mg	34	16	50
Zn	3	3	6

Source: Adapted from Dow, A.I. and Cline, T.A., Growth curve, yield, nutrient removal and petiole nutrient levels of potatoes grown on sandy soils under three center pivot irrigation systems, in *Proceedings of the 31st Annual Northwest Fertilizer Conference*, Northwest Plant Food Association, Portland, OR, 61–74, 1980.

[a] Nutrient accumulation corresponds to 95 days after emergence.

16.4 SUMMARY

Worldwide, cassava and potato are the two most economically important tuber crops. These two crops are important human food sources in developed as well as developing countries. Both these crops have a high yield potential, but current average yields are much below this potential productivity. Factors responsible for low yields, especially in the developing countries, are water stress, low soil fertility, and high incidence of diseases and pests. To overcome these constraints, a multidisciplinary research approach is necessary to develop suitable cultivars and management practices. Information provided in this chapter regarding climatic and soil requirements, growth and development, and nutrient requirements will help in understanding the crop environmental interactions and further improve our knowledge of the production systems of these two crops.

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17 Cotton

17.1 INTRODUCTION

According to the United Nations Food and Agriculture Organization, the 10 countries that produced the most cotton lint in 2007 (in million metric tons) were China (7.6), India (4.4), the United States (4.2), Pakistan (2.0), Brazil (1.4), Uzbekistan (1.1), Turkey (1.0), Syria (0.4), Turkmenistan (0.3), and Greece (0.3) (FAO, 2009). Historically, extra-long staple production has been dominated by Egypt, Sudan, and the USSR, while India, Pakistan, and China produced virtually all the short-staple cotton (Phillips, 1976). Although cotton is mostly grown for fiber, the seeds are also important. Cottonseed oil is used for culinary purposes, and the oil cake residue is a protein-rich feed for ruminant livestock.

The release of transgenic cultivars has increased cotton yields and reduced the cost of cultivation significantly in major cotton-growing countries like the United States, Brazil, India, and China. The introduction of transgenic cotton, containing genes from Bt (*Bacillus thuringiensis*) that produce proteins toxic to many insects, has dramatically reduced the need to apply insecticides for tobacco budworms, cotton bollworms, and pink bollworms (Siebert and Stewart, 2006). Transgenic glyphosate [*N*-(phosphonomethyl)glycine]-resistant cotton was commercially released with the trade name, Roundup Ready, in 1997 (Faircloth et al., 2001; Pline et al., 2001). Glyphosate, a member of the glycine herbicide family, nonselectively controls a broad spectrum of economically significant grass and broadleaf weeds by disrupting the shikimic acid pathway (Ellis and Griffin, 2002). This technology has been overwhelmingly accepted by producers with more than two-thirds of the 2003 U.S. cotton crop being planted with Roundup Ready seed (Ihrig et al., 2003). More than 95% of the 2003 North Carolina cotton crop consisted of transgenic cotton (USDA-Agricultural Marketing Service Cotton Program, 2003). Transgenic cotton is also widely grown in India, China, and Brazil. The glyphosate weed management system is an effective alternative to conventional methods, requires less herbicide and fewer applications to produce the same yield and net economic return (Culpepper and York, 1998; Nuti et al., 2006).

17.2 CLIMATE AND SOIL REQUIREMENTS

Cotton is a warm-weather plant, and the cultivated species are not tolerant of freezing temperatures. Even so, production is not limited to the tropics. Adapted cultivars and effective production techniques permit successful culture in regions where the frost-free period is less than 180 days (Niles and Feaster, 1984). Cotton is grown virtually around the world in tropical latitudes and as far north as 43°N in the USSR and 45°N in the People's Republic of China.

The ancestors of commercial cotton varieties are of tropical origin and are naturally adapted to growth in hot environments. Derived cultivars retain the high optimal temperatures for growth characteristic of their progenitors. For example, the optimal temperature for photosynthesis in the cultivar Deltapine Smooth Leaf is 25°C, with a rapid decline at lower temperatures (Downton and Slatyer, 1972). Temperature is a primary environmental factor controlling plant growth and development rates. It often determines the rate of seed germination, seedling establishment, time of flowering and fruit maturation, and growth throughout the life of the plant (Reddy et al., 1992).

Abiotic factors such as rainfall, temperature, and irradiance can alter seed and fiber development (Gerik et al., 1996; Bradow and Davidsonis, 2000; Davidonis et al., 2004; Pettigrew, 2004;

Longenberger et al., 2006; Pettigrew, 2008). The growth of cotton is very sensitive to suboptimal temperatures at all the stages of development. Temperatures below 20°C result in reduced root and shoot growth, increased days to first bloom, decreased rate of fiber elongation, and decreased fiber quality (Gipson, 1986). Reduced temperatures over the range of 25°C down to 5°C delay boll development in Paymaster and Acala cultivars (Gipson and Joham, 1968). In many temperate regions of the United States, cotton grown for fiber production experiences suboptimal day and night temperatures throughout much of the growing season. It is important to note that even moderately cool temperatures at night alone limit growth and production. On the high plains of Texas, irradiance and temperatures are optimal for cotton growth during the day, but at night, temperatures are typically 15°C–20°C, and biomass production is reduced (Burke et al., 1988). Optimum pollen germination and rapid pollen tube elongation occur between 28°C and 31°C under 80% relative humidity (Burke et al., 2004). Decreased pollen germination occurs at temperatures above 37°C, and decreased tube elongation is found at temperatures above 32°C (Burke et al., 2004). Viator et al. (2005) reported that lower and upper limits for cotton boll development are 17°C and 30°C, respectively.

The optimum temperature range for biochemical and metabolic activities of plants has been defined as the thermal kinetic window (TKW) (Burke et al., 1988). Plant temperatures either above or below the TKW result in stress that limits growth and yield. The TKW for cotton growth is 23.5°C–32°C, with an optimum temperature of 28°C, and biomass production is directly related to the amount of time that foliage temperatures are within the TKW (Burke et al., 1988; Warner and Burke, 1993).

Temperature also affects fiber quality through its effects on fiber elongation and secondary wall deposition (Pettigrew, 1995). Gipson and Joham (1969) reported that the optimum range of night temperature for maximum fiber length is 15°C–21°C, with length reductions occurring for night temperatures outside this range. They also found that micronaire, an estimate of secondary wall deposition, was reduced at night temperatures lower than 25°C.

Cotton root development is very sensitive to suboptimal soil temperatures. Cotton root length at 80 h after radicle emergence increased nonlinearly to a maximum at 32°C (Pearson et al., 1970). Taproot length of 10 day old cotton seedlings grown in soil at 20°C was 50% of the taproot length of seedlings grown at 25°C–30°C, and there was no lateral root development at 20° (McMichael and Quisenberry, 1993). The cotton taproot length of seedlings grown at 17°C was less than 40% of the length for those grown at 27°C, and root dry weight at 17°C was 68% of that at 27°C (Loffroy et al., 1983). Suboptimal soil temperatures also change the partitioning of dry matter between shoots and roots. In a review of soil temperature effects on root growth, Kaspar and Bland (1992) concluded that suboptimal soil temperatures often limit the rate of rooting depth increase and the maximum root depth of crops grown in temperate regions.

Available moisture is another key factor affecting the growth and yield of cotton. A minimum of approximately 58 cm of moisture is needed to produce a crop of 0.75 bales ha^{-1} (Waddle, 1984). The proper distribution of rainfall during the crop-growing season is also important. The water-use efficiency of harvested product averages 0.2 kg lint m^{-3}, but it can reach 0.4 kg lint m^{-3} (Hearn, 1979).

Vegetative growth is highly sensitive to water deficits. Photosynthesis and cell division continue at water potentials low enough to inhibit cell enlargement; therefore, leaf expansion is more sensitive to drought stress than photosynthesis. In general, there is linear decline in leaf expansion with decreasing leaf water potential from −1.2 to −2.4 MPa and a linear decline in photosynthesis below −2.0 MPa leaf water potential (Ackerson et al., 1977; Sung and Krieg, 1979; Karami et al., 1980). Cotton boll growth is even more tolerant to water deficits, and it is not affected until leaf water potential reaches −2.7 to −2.8 MPa (Grimes and Yamada, 1982). Hearn and Constable (1984) proposed the following classification of water stress based on leaf water potential (LWP): LWP > −1.5 MPa, minimal stress; LWP −1.5 to −2.0 MPa, mild stress; LWP −2.0 to −2.5 MPa, moderate stress; and LWP < −2.5 MPa, severe stress.

Water deficit may also lead to changes in the concentrations of several plant hormones that can induce leaf and boll abscission. Stress during flowering causes abscission of bolls and flower buds (squares), especially if the stress occurs during peak flowering. Grimes et al. (1970) reported that the

combined loss of bolls and squares due to severe stress at peak blooming caused a 32% yield loss. In contrast, severe stress, either early or late in the blooming period, gave a 20% yield loss.

According to Grimes et al. (1969), maximum seasonal evapotranspiration (ET) of cotton in the San Joaquin Valley of California reached a maximum of 72 cm when 110 cm of irrigation was applied. Yield of lint was maximum at an ET value of 68 cm. The peak daily rates of soil moisture depletion were 1.07 cm, occurring near the time when maximum leaf area was obtained. In the southern desert of California and in Arizona, actual ET for maximum production is considerably higher. For example, at Mesa, Arizona, a seasonal ET of 105 cm has been reported (Halderman, 1973), reflecting both a longer growing season and higher daily use rates. A similar seasonal ET is observed in the Imperial Valley of California (Grimes and El-Zik, 1982).

Cotton is very sensitive to waterlogging. Hodgson (1982) found that inundation during surface irrigation reduced numbers of bolls and yield by up to 20%. The reduction was correlated with the duration of anaerobiosis. Three hours of anaerobiosis kills cotton roots, compared with 5 h for soybeans (Huck, 1970).

High light intensities throughout the growing period are essential for satisfactory vegetative development, for minimal shedding of buds and bolls, and hence for high yields (Arnon, 1972). Reducing light intensity to one-third of the normal reduced carbohydrate content of the leaves by 24%, of the stems by 38%, and of the bolls by 8%, and cotton yield decreased by 47% (Eaton and Ergle, 1954).

Cotton can be grown on a variety of soils, including light sandy, heavy alluvial, and clay soils. Aeration, moisture, temperature, and a supply of nutrients are important soil factors affecting yield. Numerous studies have indicated that soil fertility and physical properties strongly affect cotton yield and fiber quality (Elms et al., 2001; Johnson et al., 2002; Ping et al., 2004). Cotton is considered as moderately acid tolerant with the lower limit of adequate pH about 5.5–6.0 (Adams, 1981). The upper pH limit for cotton growth is about 8.0. The main criterion for the suitability of soils within this pH range appears to be a depth of at least 0.6 m and freedom from prolonged waterlogging (Hearn, 1981).

Cotton is considered a salinity-tolerant crop, with a salinity threshold (for minimal yield decrease) at an electrical conductivity (EC_e) of about 7.7 dS m^{-1} (Maas and Hoffman, 1977), and a 50% reduction in yield at an EC_e of 17 dS m^{-1} (Ayers, 1977).

17.3 GROWTH AND DEVELOPMENT

Knowledge of plant structure, growth, and development is essential to improve cotton management and yield. The primary factors affecting growth are cultivar, climate, soil, pests, and cultural practices (Pettigrew and Jones, 2001). Cotton is a perennial plant, exhibiting indeterminate growth and fruiting habits and is grown as an annual crop, thereby increasing the necessity of intense management for profitable production (Cothren, 1994). Under favorable conditions, the development of *G. hirsutum* follows a rather well-defined phenological pattern (Grimes and El-Zik, 1982). As for many crops, cumulative degree days above a base temperature (at which no development occurs) are often used to predict the rate of crop development (Toscano et al., 1979). Table 17.1 presents the phenology of Acala SJ-2 and Acala SJ-5 varieties and shows the range and average calendar days and degree days (base 15.6°C) needed for each growth stage.

17.3.1 Germination and Emergence

Poor germination and seedling establishment often limit cotton plant populations and yields. Good-quality seed is the first prerequisite for ideal plant population. The value of cotton seed used for planting is determined by germination and vigor tests. Most, if not all, states in the United States require that cotton seed sold for planting purposes exhibit 80% or higher germination at 30°C, as defined by the Association of Official Seed Analysts (AOSA, 1970). Seedling vigor, defined as the potential for rapid, uniform emergence and development of normal seedlings under a wide range of field conditions (McDonald, 1980), is an additional test.

TABLE 17.1
Phenology of Cotton (*G. hirsutum*) Cultivars (Acala SJ-2 and SJ-5)

Growth Stage	Calendar Days		Degree Days (Base 15.6°C)
	Range	Average	
Sowing to emergence	5–20	10	50
Emergence to square	40–60	50	450
Square to bloom	20–27	23	330
Bloom to open boil	45–80	58	950
Normal crop production	190–210	200	>2800

Sources: El-Zik, K.M. and Sevacherian, V., Modeling cotton growth and development parameters with heat units, in *Proceedings of the Beltwide Cotton Production Research Conference*, National Cotton Council, Memphis, TN, 1979; El-Zik, K. et al., The effect of management on blooming boll-retention, and productivity of upland cotton (*Gossypium hirsutum* L.), in *Proceedings of the Beltwide Cotton Production Research Conference*, National Cotton Council, Memphis, TN, 1980.

Cotton seed germination is complicated by water uptake and chilling problems. The cotton seed is covered by a dense mat of fuzz fibers (linters), by a heavy seed coat with a chalazal cap opening mechanism, and by a thin layer of endosperm (McArthur et al., 1975). An impermeable seed coat and the impenetrability of seed coat fibers by water are the two major factors inhibiting cotton seed germination. It is generally recommended that fuzzy seeds should be delinted by machine, flame, or sulfuric acid (Cherry and Leffler, 1984).

Under favorable conditions, seedlings emerge 5–15 days after sowing. The rates of elongation of the radicle and hypocotyl are controlled by temperature and soil water potential. Wanjura et al. (1970) found that the temperature limits were 14°C–42°C with an optimum 34°C. At optimum temperatures, seedlings emerged in 5 days at −0.03 MPa, in 7 days at −0.3 MPa, and did not emerge in 13 days at −1.0 MPa (Wanjura and Buxton, 1972). Even if seeds germinate well, soil crusting can adversely affect seedling emergence.

17.3.2 Root System

Within the seed, the radicle is larger than the epicotyl, and even before true leaves begin expanding, the primary root is penetrating deeply into the soil and branch roots are being formed (Mauney, 1984). The cotton plant has a primary taproot with many lateral roots. The main absorption and anchoring structure of the cotton plant is the mass of roots that branch from the taproot. The depth of primary root penetration depends on soil, climate, and genotype. Borg and Grimes (1986) calculated the rooting depth of cotton based on various root growth data in the literature and came to the conclusion that maximum root depth of cotton is 150–300 cm under favorable conditions. Root length density and dry weight decrease exponentially with depth. The depletion of water in the upper profile can lead to the proliferation of roots at depth, resulting in greater extraction of water at depth (Klepper et al., 1973). The general development of the cotton root system has been described by Taylor and Klepper (1978), Grimes and El-Zik (1982), and McMichael (1986).

Root growth is a dynamic process responding to signals from both the soil environment and the shoot. Abiotic and biotic stresses reduce root growth, ultimately limiting shoot development and yield potential (Burke and Upchurch, 1995). Soil factors known to alter root growth include soil temperature, structure, water, oxygen, and nutrient availability (Bowen, 1991). Genetic diversity in root growth

between and within species has been identified, and genotype × environment interactions have been reported (Bland, 1993; Engels, 1994). Temperature is a universal factor for regulating cellular growth and development. Temperature influences not only root proliferation, but also root function. For example, root temperature affects the plant's hydraulic conductivity, nutrient uptake, and the synthesis and transport of regulatory hormones (Clark and Reinhard, 1991; Bolger et al., 1992; Engels, 1994).

17.3.3 Stem and Leaves

The main stem of the cotton plant is monopodial, with leaves and branches but no flowers. There are usually two axillary buds at each main stem node, the second branching off the first. Normally, only one bud develops. At lower nodes, the first bud remains vegetative and may develop into a vegetative branch of monopodium that is a replica of the main stem (Hearn and Constable, 1984). Usually, the vegetative branches occur in a definite zone near the base of the plant, and the fruiting branches occur farther up the stem. The number of nodes from the base of the main stalk to the first fruiting branch varies considerably among cotton species and is affected by cultural practices.

The leaves of most American cotton varieties have five more or less clearly defined lobes. The blade is usually large, thin, and relatively hairy, although smooth leaf types exist. Its surface contains many stomata through which gases are exchanged between the plant and the surrounding atmosphere. Most of the stomata are on the underside of the leaf. The petiole is usually about as long as the leaf blade. At the point where it joins the stem or branch, it is flanked by two small stipules (Tharp, 1965).

17.3.4 Fruit Development

Development of the cotton fruit (boll) involves a complex series of events and interactions that begin with the appearance of the first flower bud (square) and continue until the boll opens. The pollination of a cotton flower generally takes place on the first day the flower opens. The majority of the flowers are self-pollinated, but cross-pollination occurs if bees and other insects are active. Normally, cross-pollination ranges from 6% to 25%, but over 50% has been reported (Purseglove, 1982). After anthesis, the boll develops from a superior ovary consisting of 3–5 carpels united into a tough-walled capsule. Internally, it is divided into 3–5 locules, each of which initially contains 10–12 ovules, 5–11 of which develop into seeds covered with fiber (Hearn and Constable, 1984). The contents of one mature locule forms a lock of seed cotton. The number of ovules per boll is influenced by genetic and physiological factors, especially nitrogen supply (Hughes, 1966). It is natural for some squares, blooms, and small bolls to be shed. Shedding is increased by such factors as moisture deficiency, an inadequate number of fertilized ovules, an insufficient nutrient supply, excessive heat or cold, and damage from insects and diseases (Grimes and El-Zik, 1982).

Flower and fruit (boll) retention is high early in the reproductive phase but usually decreases with increasing fruit load. Pronounced decreases in vegetative growth, flowering, and boll retention are commonly referred to as cutout (Patterson et al., 1978). If cutout occurs before the end of the growing season, yield may be below what it would have been if the crop had utilized the entire growing season. Conversely, cutout at the end of the season is desirable because it facilitates harvest and deprives insect pests of a food source before they enter diapause (Kittock et al., 1973). Fruit load appears to be a major factor affecting cutout. As plants become loaded with bolls, growth and flowering rates slow and boll retention decreases (Patterson et al., 1978). These effects could result from competition for photosynthate, a change in hormonal status, or both. Guinn (1982) suggested that nutritional stress increases boll shedding (an important aspect of cutout) through an increase in ethylene production. In another study, Guinn (1985) suggested that growth, flowering, and boll retention decrease when the demand for photosynthate increases and exceeds the supply. This suggests that an increase in photosynthesis should permit more bolls to be set before cutout.

Two types of fibers cover the seed surface of most upland cotton cultivars: The long lint fibers that are used in the manufacture of fabrics and the short fuzzy fibers, sometimes called linters, that

TABLE 17.2
Developmental Events in Relation to Days Before and After Anthesis

Age	Events
−40	Floral stimulus.
−32	Carpel and anther number established.
−23	Ovule number established.
−22	Pollen mother cell meiosis; "pin-head square."
−14	Megaspore mother cell meiosis.
−7	Begin exponential expansion of corolla.
−3	Begin fiber differentiation.
0	Flower open; pollen shed, germinates; fiber initiation; K accumulation in fiber.
+1	Fertilization of egg and polar nuclei; division of primary endosperm nucleus; zygote shrinks.
+2	Liquid endosperm developing; fibers begin elongating; most dry mass goes to fibers.
+3 to 4	Zygote divides.
+5 to 6	Ovule integument division stops; fuzz fibers uninitiated; globular embryo dividing but not increasing in size; ovule enlargement stage proceeding rapidly; dry mass to internal parts increases.
+12 to 13	Endosperm becomes cellular around embryo; palisade cells elongate; embryo differentiation begins.
+14 to 16	Secondary deposition in fibers, outer integument and palisade begins; embryo elongating, accumulates Ca and Mg; fibers begin slow accumulation of Ca; outer integument begins rapid weight increase.
+20	Endosperm completely cellular and at maximum weight; fiber elongation slows rapidly; P translocated from fiber; embryo begins accumulating protein; weight distribution about equal between fiber and embryo.
+25	Fiber elongation complete; bur weight maximum; cotyledons complete; embryo maximum length; endosperm declining; oil accumulation starts.
+30 to 32	Embryo enters period of grand weight gain; endosperm nearly depleted; maximum rate of cellulose deposition in fiber, oil, and protein in embryo; rapid P and K accumulation in embryo; fibers begin losing K.
+42	Dry weight of boll nearly maximum; some oil accumulation; fibers lose Mg; cellulose deposition stops.
+45 to 50	Internal changes in seed hormones and enzymes; seed coat hardens; boll sutures dehisce in response to ethylene.

Source: Adapted from Stewart, J.M., Integrated events in the flower and fruit, in *Cotton Physiology*, Mauney, R. and Stewart, J.M. (eds.), The Cotton Foundation, Memphis, TN, 261–300, 1986.

form a dense mat near the surface of the seed (Quisenberry and Kohel, 1975). Each cotton fiber, actually a trichome, is formed from a single cell in the outer cell layer of the seed coat. Fiber initiation begins when approximately 25% of the ovular epidermal cells differentiate into lint fiber cells. Each ovule produces approximately 13,000–21,000 lint fiber cells, which elongate for about 15–25 days after anthesis. After slightly more than 2 weeks of lengthening, fiber cells' secondary wall deposition begins. The successive layers of cellulose are deposited until the wall is 3–4 μm thick. At approximately 45–60 days after anthesis, the seed capsule dehisces and the thin fiber cells quickly dehydrate. As the cytoplasm dries, it adheres to inner fiber cell wall, leaving a lumen where the central vacuole was once located (Kim and Triplett, 2001).

A summary of the sequence of events from flower induction to boll opening in relation to days before and after anthesis is presented in Table 17.2. The timing of events described in Table 17.2 is approximate and can change with environmental conditions.

17.3.5 Dry Matter Production

The dry matter production of cotton is influenced by climate, soil, and plant factors. Olson and Bledsoe (1942) determined the dry matter production during various growth stages of cotton grown on three different soil types. On all three soils, the largest percentage of dry matter was produced during the period from early boll formation to maturity. Total dry matter production ranged from

5.6 to 10.9 t ha^{-1}. Oosterhuis et al. (1983) reported that about 60% of the total dry matter was produced between 10 and 16 weeks after sowing at two locations in Zimbabwe. Total dry matter production was 8.5 t ha^{-1} at maturity (150 days after sowing).

Most of the research devoted to cotton growth and development has centered on upland rather than Pima (*G. barbadense* L.) cotton (Unruh and Silvertooth, 1996). Wells and Meredith (1984a–c) conducted a series of studies to compare the growth of obsolete and modern upland cotton cultivars. They found that an increase in the number of harvestable bolls was the major component contributing to greater yield of modern upland cultivars (Wells and Meredith, 1984c). Wells and Meredith (1984b) found that modern upland cultivars produce larger lint yields primarily by (1) a greater partitioning of dry matter to reproductive organs and (2) an increased amount of reproductive development occurring when maximal leaf mass and area are present. The results of a later study (Meredith and Wells, 1989) suggested that further yield increases in upland cotton by conventional breeding methods would likely be achieved through the continued partitioning of dry matter from vegetative to reproductive plant structures. Other recent studies have been conducted to describe dry matter accumulation by upland cotton under both dryland (Mullins and Burmester, 1990) and irrigated conditions (Bassett et al., 1970; Halevy, 1976).

When ground cover is complete, cotton growth rates range from 15 to 20 g m^{-2} day^{-1}. The growth rate of a square is exponential, its weight increasing from about 10 to 130 mg in the 4 weeks prior to flowering (Hearn and Constable, 1984). According to Mutsaers (1976), boll weight follows a sigmoid pattern, with a maximum growth rate of 0.28 g day^{-1} about 20 days after flowering.

At boll maturity, the total dry weight of a boll (4–10 g) is typically 18% boll wall and bracts, 48% seed, and 34% lint. Cotton seed is about 22% protein and about 22% oil (Hearn and Constable, 1984). Lint generally forms 20%–40% of the material transported to the gin, depending on whether the cotton is stripped or picked and on the type of harvester used. After the seed cotton is ginned (the long fibers are separated from the seed), the lint is packed in bales weighing approximately 218 kg for transport (Perkins et al., 1984).

17.3.6 Leaf Area Index

According to Hearn and Constable (1984), peak LAI occurs 3–5 weeks after the start of flowering and varies from 0.5 for a severely water-stressed crop to more than 6 for a well-fertilized and irrigated crop grown in a warm area. In the High Plains of Texas (USDA/ARS, 1988), LAI increased in a sigmoid manner, reaching maximum values in excess of six on an irrigated sandy soil under 100% ETa replacement. The maximum LAI on a clay loam soil was slightly greater than 3. Plants at both locations achieved maximum LAI in 70–80 days after sowing, a time which coincided with peak flower production.

17.3.7 Photosynthesis

The photosynthetic rate of a crop is the product of the amount of light intercepted and the efficiency of the intercepting tissue (Hesketh and Baker, 1967). Percent light interception depends on solar angle and canopy geometry. Efficiency is often constant over considerable periods of time; however, most studies of cotton photosynthesis have been done under greenhouse or growth chamber conditions, where rates may differ from those measured under field conditions (Bjorkman and Holmgrin, 1963).

The potential rate of net photosynthesis of individual cotton leaves is approximately 130 mg CO_2 cm^{-2} s^{-1} (30 µmol CO_2 m^{-2} s^{-1}) for a recently fully expanded leaf on a plant well supplied with water and nutrients, at ambient CO_2 levels, about 30°C leaf temperature, and at light saturation (quantum flux 2000 µE m^{-2} s^{-1}) (Hearn and Constable, 1984). Growing cotton plants in atmospheres enriched with CO_2 indicates that yield can be regulated by photosynthesis (Mauney et al., 1978). Cotton plants grown at 620 mg kg^{-1} CO_2 showed an initial increase in CO_2 exchange rate

of 65% (which later declined to 31%) compared to plants grown at 330 mg kg^{-1} CO_2 (Benedict, 1984). The CO_2 compensation point of cotton leaves is 70 μL L^{-1}, indicating that cotton, like other C_3 plants, exhibits photorespiration (Benedict et al., 1972). Similarly, Hesketh (1967) showed that the photosynthetic rate of Acala B-54 cotton leaves was enhanced 38% by O_2-free air due to photorespiration.

17.4 YIELD AND YIELD COMPONENTS

World mean cotton yields have increased rather consistently from 234 kg ha^{-1} in 1950–1951 to 299 kg ha^{-1} in 1961–1962, 380 kg ha^{-1} in 1970–1971, 426 kg ha^{-1} in 1980–1981, 572 kg ha^{-1} in 1990–1991, 604 kg ha^{-1} in 2000–2001, and 715 kg ha^{-1} in 2006–2007 (Bowling, 1984; USDA-FAS, 2009a). Production in the United States was about 294 kg ha^{-1} or slightly less, from around 1870–1935 (Lewis and Richmond, 1968). By 1968, yields of lint in the United States had reached 561 kg ha^{-1}, a twofold increase in 30 years (Lee, 1984). Since that time, average yields increased to 586 kg ha^{-1} in the 1980–1989, 723 kg ha^{-1} in the 1990–1999, and 866 kg ha^{-1} in the 2000–2009 (USDA-FAS, 2009b). Breeding has played a significant role in modifying cotton plant structures and increasing pest resistance. The first step in yield improvement was the development of the annual habit in a perennial shrub. This was accompanied by the loss of photoperiod sensitivity in most cases, lowering the nodal position of the first fruiting branch, and reduction in the amount of facultative bud shedding in wet weather (Hearn and Constable, 1984). The recent development of transgenic cultivars with increased insect and herbicide resistance have also contributed to increased average yields.

The yield components of cotton are bolls per plant, seed per boll, boll weight, and lint percentage. The number of bolls per plant is the most important yield variable (Wu et al., 2005). Both genotypic and environmental differences in cotton lint yield are often associated with the number of mature bolls per unit area rather than lint per boll (Wells and Meredith, 1984c; Heitholt et al., 1992; Heitholt, 1995). The number of mature bolls per unit area is a product of the number of flowers produced per unit area and the fraction of flowers that produce mature bolls (boll set or boll retention). Heitholt (1993) reported that high-yielding cultivars produced 16% more flowers (seasonal total number of flowers produced per unit area) than a low-yielding experimental line. Likewise, the high-yielding cultivars had higher boll retention (48%) than a low-yielding experimental line (42%). Cook and El-Zik (1993) reported that yield increases due to irrigation were associated with both increased flower production and boll retention.

Morrow and Kreig (1990) studied the effects of water and N supply on plant density, bolls per plant, and average boll size. Regression analysis revealed that lint yield was most highly correlated with boll number per unit area, with equal contributions from plant density and bolls per plant. Boll number was most responsive to water supply; however, within each H_2O regime, increasing N supply increased boll number per plant. Multiple regression analysis revealed that lint yield was more responsive to water and N supplies during the fruiting period than prior to flowering.

17.5 NUTRIENT REQUIREMENTS

Sound nutrition is one ingredient of high field crop yields, including cotton. Nutrition affects the yield of cotton to a far greater extent than it affects lint quality, which is largely determined by genotype and weather (Hearn, 1981). Since cotton production covers a wide range of environments and economic circumstances, yields and hence nutritional requirements vary greatly.

Cotton nutrition is influenced by several characteristics that distinguish the nutrient requirements of cotton from those of other field crops. First, cotton is a tropical perennial shrub that is grown as an annual crop. Indeterminate growth habit and vegetative branching provide an infinite number of potential fruiting sites unless growth is limited by low temperatures, lack of water, insufficient supply of nutrients or carbohydrates derived from photosynthesis, or other limiting factors. Second, the cotton plant has a deep taproot system with unusually low root density in the surface soil layer

where available nutrient levels are greatest. This rooting pattern makes the cotton plant more dependent on nutrient acquisition from subsoil than most other crop plants (Cassman, 1993). The diagnosis of nutrient disorders of cotton often requires the evaluation of subsoil conditions, particularly where subsoils are low in potassium or calcium or exhibit aluminum toxicity. Finally, unlike most annual field crops, the yield of lint (a cellulose fiber) rather than seed determines the economic value of the crop. The deficiencies of certain nutrients reduce fiber quality as well as plant growth and lint yield (Cassman, 1993).

Hearn (1981) has summarized the relative frequency of nutrient deficiencies for different agroclimatic regions in the early 1980s. During this period, N deficiency was very common; P and K deficiencies were common; Mg, S, Zn, B, and Mn deficiencies were occasional; deficiencies of Ca, Fe, and Cu were rare; and Mo and Cl deficiencies were unknown. Inadequate fertilization is still one of the main reasons for low cotton yields, especially in developing countries (Malavolta et al., 2004; Fontes et al., 2008; Janat, 2008). A sample survey on fertilizer practices in the selected districts of various states in India showed that only 7%–20% of the irrigated area received fertilizers.

Fertilizer N recommendations vary substantially, depending on potential yields and whether the crop is irrigated. As cultivar yield potentials have increased, so have N requirements. For example, average N recommendations for California upland cotton increased from 120 kg ha^{-1} in the late 1970s to about 200 kg ha^{-1} by the mid 1990s (Fritschi et al., 2003). Current management strategies for San Joaquin Valley cotton production call for N applications ranging from 171 to 228 kg ha^{-1} (Hutmacher et al., 2004). In some cases, annual N application for cotton may exceed 228 kg ha^{-1} (Weir et al., 1996; Hutmacher et al., 2004).

Conventional row spacing of cotton in the United States ranges from 76 to 102 cm (Clawson et al., 2006, 2008). Wiatrak et al. (2005) reported that maximum lint yield of cotton was achieved with 105 kg N ha^{-1} in a conventional tillage system. Clawson et al. (2006) reported that cotton yield was significantly increased with increasing N rate in the range of 0–151 kg ha^{-1} but did not find differences in the row spacing between 19, 38, and 76 cm, respectively. However, Rinehardt et al. (2003) and Boquet (2005) reported that in ultra-narrow row spacing (UNR) (25 cm or less) optimum yields required only 90 kg N ha^{-1}. Reiter et al. (2008) recommended 126 kg N ha^{-1} as ammonium nitrate in broadcast applications split between planting and first match head square. The nitrogen requirements of cotton can be reduced by using legume cover crops in rotation with cotton (Schomberg et al., 2006). The value of legumes as a source of N for subsequent crops has been well documented (Reeves, 1994), and substantial work in this area has been conducted with modern cotton cultivars (Daniel et al., 1999; Larson et al., 2001; Bauer and Roof, 2004).

The deficiencies of essential nutrients reduce plant growth and yield. A deficiency of one group of nutrients (P, K, Ca, Mg, B, and Zn) limits fruit production to a greater extent than vegetative growth, whereas deficiency of a second group of nutrients (N, S, Mo, and Mn) restricts vegetative and fruiting growth to an equal extent (Benedict, 1984; Hitsuda et al., 2005). Most of the nutrients in the first group may affect fruiting efficiency because they function in the control of carbohydrate translocation.

Potassium deficiency affects photosynthesis in cotton (Bednarz et al., 1998; Zhao et al., 2001) and has a detrimental effect on yield and fiber quality (Pettigrew and Meredith, 1997; Read et al., 2006). Increasing K supply in irrigated cotton led to significant improvements in yield and fiber quality (mainly fiber length) (Cassman et al., 1990). Lopez et al. (2008) reported a response of dryland cotton to K fertilization, and K deficiency symptoms have recently been reported in increased frequency throughout the U.S. cotton production regions (Pettigrew et al., 1996; 2005; Clement-Bailey and Gwathmey, 2007). Potassium deficiency in cotton is responsible for yield reductions averaging 15%–20% in California (Cassman et al., 1989) and is also a major concern of producers in the U.S. Southwest (Reeves and Mullins, 1995). This observation has coincided with the increased use of early-maturing and high-yielding genotypes, leading some researchers to speculate that genotype development has affected the K response (Oosterhuis et al., 1991). Because the root system of cotton is less dense than that of other crops (Gerik et al., 1987), it has been suggested that the

rooting systems of these fast-fruiting genotypes were unable to supply the K requirements during boll growth because the bolls are a major sink for K (Leffler and Tubertini, 1976), and cotton root growth slows during boll development (Pearson and Lund, 1968).

Generally, fertilizer recommendations are based on soil and/or plant analyses. These tests are usually specific to particular soils, climates, and yield levels and cannot be extrapolated easily to other areas. Therefore, in this section, no attempt has been made to give detailed fertilizer recommendations. All cotton-growing states in the United States and essentially all cotton-growing countries of the world provide soil testing services for cotton growers (Melsted and Peck, 1973). However, some basic principles of mineral nutrition, nutrient uptake, and concentration are discussed to provide guidelines in understanding cotton nutrient requirements.

17.5.1 Nutrient Uptake

The soil–plant system is a dynamic system, and the uptake of nutrients is influenced by several factors. It is very difficult to know the exact amounts of nutrients required by a crop. However, the amounts of nutrients removed in the economic yield are an indication of the crop's nutritional requirement. Nutrient uptake or accumulation is related to yield level. Nitrogen, phosphorus, and potassium are the nutrients removed in the greatest amounts. Cotton yielding 2.5 bales ha^{-1} (1 bale = 218 kg approximately) removes approximately 40 kg N ha^{-1}, 7 kg P ha^{-1}, 14 kg K ha^{-1}, 4 kg Mg ha^{-1}, and 3 kg Ca ha^{-1} (Berger, 1969). With 3.75 bales ha^{-1} yields, 62, 11, 22, 7, and 4 kg ha^{-1} of N, P, K, Mg, and Ca, respectively, are removed. A yield of 7.5 bales ha^{-1} removes approximately 125, 22, 43, 13, and 9 kg ha^{-1} of the same nutrients. According to Malavolta et al. (1962), for every 100 kg of fibers produced, the cotton crop will require approximately 19 kg of N, 8 kg of P, 15 kg of K, 15 kg of Ca, and 4 kg of Mg under Brazilian conditions.

Under field conditions, Mullins and Burmester (1992) evaluated the uptake of Ca and Mg by four cotton cultivars grown on two nonirrigated soils containing adequate levels of Ca and Mg, using cultural practices that are normal for the southeastern United States. Plants were collected at 2 week intervals throughout the growing season, beginning at 15 days after emergence, were partitioned into leaves, stems, burs, seed, and lint, and were analyzed (except for lint) for Ca and Mg. Total Ca and Mg uptake, when averaged for both soils and all four cultivars, was 64 and 18 kg ha^{-1}, respectively (or 9.3 kg of Ca and 2.6 kg Mg per 100 kg lint produced). Total Ca uptake was significantly lower on the Norfolk soil (44 kg ha^{-1}) as compared to the Decatur soil (75 kg ha^{-1}) that had a higher level of extractable Ca. There were no cultivar differences in total Ca and Mg uptake or uptake within a given plant part. There were no consistent differences among the cultivars for the concentration of Ca in various plant parts. The concentration of Mg in leaves and burs was affected by the cultivar. These cultivars accumulated similar amounts of Ca and Mg as compared to older cultivars, although previous research had shown that modern cultivars partition dry matter differently than older cultivars (Mullins and Burmester, 1992).

The apparent recovery of N by a cotton crop averages about 40% of the applied N and is seldom greater than 50% (Weier, 1994). Factors identified as affecting recovery include water stress, crop rotation, waterlogging, and soil compaction, the latter two having considerable influence on the loss of fertilizer N through biological denitrification.

The distributions of N, P, K, Ca, Mg, and Mn among the bur (carpel walls), seed, and fiber fractions of cotton bolls were measured between 10 days after flowering and boll maturity by Leffler and Tubertini (1976). During the initial 3 week phase of boll enlargement, the bur accumulated reserves of N, P, and Mg, which were drawn upon, presumably by the seed and fiber, during later development. The bur continuously accumulated K, which reached 5.5% at maturity. The concentrations of most minerals in the seed declined initially and then increased markedly. The major mineral accumulated by the seed was N. At boll opening, over 90% of boll N was in the seed. The fiber accumulated minerals during the first 5 weeks of development but lost most of them during the final 3 weeks. The most abundant mineral in the fiber was K.

TABLE 17.3
Adequate Nutrient Concentration in Cotton

Nutrient	Growth Stage[a]	Plant Part[a]	Adequate Concentration ($g\ kg^{-1}$)
N	45 DAS	LB at third and fourth nodes below A	>50
	First flowering	YMB	38–45
P	45 DAS	LB at third and fourth nodes below A	>4
	First flowering	YMB	3–5
	Early fruiting	YMB	3.1
	Late fruiting	YMB	3.3
	Late maturity	YMB	2.4
K	45 DAS	LB at third and fourth nodes below A	>32
	76 DAS	PYMB	49–62
	101 DAS	PYMB	46–60
	120 DAS	PYMB	25–40
Ca	First flowering	YMB	22–30
Mg	First flowering	YMB	5–9
	34–105 DAS	All LB	6–8
	34–105 DAS	All P	4–7
S	Midseason	YMB	6–10
			$mg\ kg^{-1}$
Zn	First flowering	YMB	20–60
	43 DAS		17–18
Mn	First flowering	YMB	50–350
	36 DAS	YMB	11–247
Fe	First flowering	YMB	50–250
B	First flowering	YMB	20–60
Mo	5 months	LB	2.4

Source: Compiled from Reuter, D.J., Temperate and sub-tropical crops, in *Plant Analysis: An Interpretation Manual*, Reuter, D.J. and Robinson, J.B. (eds.), Inkata Press, Melbourne, Australia, 38–99, 1986.

[a] DAS, days after sowing; LB, leaf blade (excluding sheath and petiole); YMB, youngest (uppermost) mature leaf blade; P, petiole.

17.5.2 Nutrient Concentration

Nutrient concentrations in plant parts have been used to evaluate fertilizer practices and to investigate problems of poor growth. Their most promising role appears to be in assessing the adequacy of plant nutrient supply for cotton during the growing season (Sabbe and Mackenzie, 1973). Adequate nutrient concentrations in cotton plant parts at different growth stages are presented in Table 17.3. Since cotton culture involves the growth of many varieties in different soil, climatic, and management environments, sufficiency levels can be expected to vary somewhat among regions.

17.6 SUMMARY

Cotton is a major fiber crop in developing as well as developed countries. The cotton plant is a warm-season perennial shrub that is grown as an annual field crop between 47°N and 32°S latitude. The top five cotton-producing countries are the People's Republic of China, India, the United States, Pakistan, and Brazil. Cotton provides about 25% of the fibers for the world market, while synthetic and other natural fibers provide the remaining 75%. Still, cotton is an agricultural and industrial

commodity of worldwide importance, and growing worldwide consumption ensures that it will continue to be a significant commodity in the future. In addition, interest in the potential of cotton seed as a source of edible vegetable protein has been stimulated by increased understanding of its constituents and processing methods.

The optimum temperature for cotton growth is 24°C–34°C. It can be grown on a variety of soils, from sandy to clayey, with pH from 4.3 to 8.4, though the optimum pH range is 5.0–7.0. Maximum lint yields may be greater than 2 metric tons ha^{-1} in irrigated areas with very long growing seasons; however, world average lint yields are currently about 0.7 tons ha^{-1}.

Cotton lint is almost pure cellulose and contains negligible amounts of N, P, and K. However, cotton seed contains about 3.7% N, 0.55% P, and 0.95% K. In addition, cotton burs contain significant amounts of nutrients. Thus, fertilizers or manures are usually required to replace nutrients removed in the seed and burs. Both soil and plant analyses can be used to detect and correct nutrient deficiencies and toxicities.

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18 Forage

18.1 INTRODUCTION

Climatic and edaphic factors are the major determinants of the distribution and production of plants, in both natural and managed ecosystems (Andrew, 1978). Forage grasses and legumes can grow under a wide range of climatic and soil conditions. It is impossible to discuss climatic and soil requirements for all 11,000 grass and legume species used as forages worldwide (Janick et al., 1969). However, some basic principles of soil and climatic responses of forages have widespread applicability and are discussed in this section. The characteristics of important grass and legume species are listed in Table 18.1. These grasses and legume species are the important forage species in the tropical, subtropical, and temperate regions around the world.

Seasonal drought is a dominant feature of most grassland environments; therefore, adapted forage species must be able to tolerate considerable soil water deficits (Trewartha et al., 1967; Bula, 1982; Cochrane et al., 1985). Rao et al. (1992) found that tropical forage grasses differ in their responses to drought, and several of the most common grasses, including *Brachiaria* spp., *Andropogon gayanus*, and *Panicum maximum*, are tolerant of seasonal droughts (CIAT, 1978). Similarly, tropical forage legume species vary in their response to water stress, including the minimum plant water potential reached during extended drought and the number of weeks to achieve it (Table 18.2). Water potential is a measure of physiological water deficit in plant tissue (Hsiao, 1973). Well-watered plants usually have leaf water potentials around 0 to −5 MPa. Most crop plants tolerate water deficits up to −20 MPa in leaves. Compared with most field crops, tropical forage legumes seem to tolerate much lower water potentials. For example, both *Stylosanthes capitata* and *Desmodium ovalifolium* are outstandingly tolerant of water stress. In contrast, the water potential of *Centrosema brasilianum* is relatively high (less negative value). Tolerance of soil water deficits was greater (the minimum water potential was less) in *Arachis pintoi* than in *C. brasilianum*. These two species may have contrasting physiological mechanisms to tolerate (*A. pintoi*) or avoid (*C. brasilianum*) leaf water deficits. These data illustrate the broad range of adaptation to water stress found in the forage legumes.

Grasses adapted to warm tropical or warm-season subtropical and temperate climates have a higher optimum temperature for dry matter production than high-altitude tropical and cool-season temperate grasses. Optimum temperatures for tropical grasses adapted to warm climates are in the range of 30°C–40°C as compared to 20°C–30°C for many temperate grasses (Jones, 1985; Rotar and Kretschmer, 1985). Optimum temperatures for tropical pasture legumes vary from 25°C to 30°C, while for many temperate legumes the optimum temperatures are in the range of 20°C–25°C (Rotar and Kretschmer, 1985). Growth of most tropical grasses and legumes is significantly reduced below 15°C, and these species are susceptible to frost. On the other hand, temperate forage species are tolerant to frost, although their growth rates decline at lower temperatures (Rotar and Kretschmer, 1985; Brandsaeter et al., 2002; Evers and Smith, 2006). Table 18.3 shows tolerance of some grass and legume forage species to drought, frost, and waterlogging and gives their minimal annual rainfall requirements.

Most of the pasture grasses and legumes do well in deep and well-drained soils with high water-holding capacity. Forage grasses and legumes have shown a wide range of adaptability to soil pH (Evers, 2003). Table 18.4 shows the adaptability of several warm and cool season grass and legume species to various soil pH ranges. Optimum soil pH in general for forage legumes and grasses is in the range of 5–7.

Figure 18.1 shows that high levels of Al at low pH can significantly reduce the growth of grasses. When Al concentration was more than 1 cmol kg^{-1} of soil, relative yield was less than 50%.

TABLE 18.1
Some Important Forage Grasses and Legumes

Common Name		Scientific Name	Annual (A) or Perennial (P)	Photosynthetic Path	Cool (C) or Warm (W) Season
Grasses	Bahiagrass	*Paspalum notatum* Flugge	P	C_4	W
	Bermudagrass	*Cynodon dactylon* (L.) Pers.	P	C_4	W
	Bromegrass	*Bromus inermis* Leyss.	P	C_3	C
	Buffelgrass	*Cenchrus ciliaris* (L.) Link	P	C_4	W
	Dallisgrass	*Paspalum dilatatum* Poir.	P	C_4	W
	Gambagrass	*Andropogon gayanus* Kunth	P	C_4	W
	Guineagrass	*Panicum maximum* Jacq.	P	C_4	W
	Italian ryegrass	*Lolium multiflorum* Lam.	A	C_3	C
	Jaragua	*Hyparrhenia rufa* (Nees) Stapf.	P	C_4	W
	Kentucky bluegrass	*Poa pratensis* L.	P	C_3	C
	Kikuyugrass	*Pennisetum clandestinum* Hoschst.	P	C_4	W
	Kleingrass	*Panicum coloratum* Walt.	P	C_4	W
	Limpograss	*Hemarthria altissima* (Poir) Stapf. & Hubbard	P	C_4	W
	Napiergrass	*Pennisetum purpureum* Schumach	P	C_4	W
	Orchardgrass	*Dactylis glomerata* L.	P	C_3	C
	Pangolagrass	*Digitaria decumbens* Stent.	P	C_4	W
	Paragrass	*Brachiaria mutica* (Forsk) Stafp.	P	C_4	W
	Perennial ryegrass	*Lolium perenne* L.	P	C_3	C
	Reed canarygrass	*Phalaris arundinacea* L.	P	C_3	C
	Redtop	*Agrostis alba* L.	P	C_3	C
	Rhodesgrass	*Chloris gayana* Kunth.	P	C_4	W
	Speargrass	*Heteropogon contortus*	P	C_4	W
	Sudangrass	*Sorghum bicolor* drummondi	A	C_4	W
	Surinamgrass	*Brachiaria decumbens* Stapf.	P	C_4	W
	Switchgrass	*Panicum virgatum* L.	P	C_4	W
	Tall fescue	*Festuca arundinacea* Schreb.	P	C_3	C
	Timothy	*Phleum pratense* L.	P	C_3	C
	Crested wheatgrass	*Agropyron cristatum* (L.) Gaertn.	P	C_3	C
Legumes	Alfalfa	*Medicago sativa* L.	P	C_3	C
	Birdsfoot trefoil	*Lotus corniculatus* L.	P	C_3	C
	Blue lupine	*Lupinus angustifolius* L.	A	C_3	C
	Centro	*Centrosema pubescens* Benth	P	C_3	W
	Common vetch	*Vicia sativa* L.	A	C_3	C
	Common lespedeza	*Lespedeza striata* Hook & Arn	A	C_3	W
	Flatpea	*Lathyrus sylvestris* L.	A	C_3	C
	Hairy vetch	*Vicia villosa* Roth	A	C_3	C
	Kudzu	*Pueraria thunbergiana* Benth	P	C_3	W
	Ladino clover	*Trifolium repens* L.	P	C_3	C
	Red clover	*Trifolium pratense* L.	P	C_3	C
	Silverleaf desmodium	*Desmodium uncinatum* Jacq	P	C_3	W
	Sub clover	*Trifolium subterraneum* L.	A	C_3	C
	Townsville stylo	*Stylosanthes humilis* H.B.K.	A	C_3	W
	White lupine	*Lupinus albus* L.	A	C_3	C
	White sweet clover	*Mclitus alba* Med.	P	C_3	C
	Yellow lupine	*Lupinus luteus* L.	A	C_3	C
	Yellow sweet clover	*Melilotus officinalis* Lam.	P	C_3	C

TABLE 18.2
Water Stress Tolerance of Tropical Forage Legumes

Legume Species	Minimum Water Potential (MPa)	Time to Reach Minimum Water Potential (weeks)
Stylosanthes capitata	−65.9	21.5
Desmodium ovalifolium	−65.7	14.8
Arachis pintoi	−61.9	13.3
Centrosema acutifolium	−60.8	13.2
Centrosema brasilianum	−28.9	16.8
Standard error of means	5.4***	1.0***

Source: Rao, I.M. et al., Soil-plant factors and processes affecting productivity in ley farming, in *Pastures for the Tropical Lowlands: CIAT's Contribution*, CIAT (ed.), CIAT, Cali, Colombia, 145–175, 1992.

*** $P < 0.001$.

TABLE 18.3
Tolerance of Selected Tropical Grass and Legume Species to Drought, Frost, and Waterlogging

		Tolerance Rating			
Species		Frost	Drought	Waterlogging	Minimum Annual Rainfall (mm)
Grasses	*Andropogon gayanus*	Poor	Good	Good	400
	Brachiaria decumbens	Poor	Fair	Fair	1250
	Brachiaria mutica	Poor	Fair	Excellent	1000
	Cenchrus ciliaris	Fair	Excellent	Poor	300
	Cynodon dacrylon	Poor	Excellent	Poor	500
	Digitaria decumbens	Poor	Fair	Good	1000
	Eragrostis curvula	Fair	Good	Poor	500
	Hemarthria altissima	Poor	Fair	Good	1000
	Hyparrhenia rufa	Fair	Good	Poor	600
	Melinis minutiflora	Poor	Fair	Poor	900
	Panicum antidotale	Fair	Excellent	Fair	400
	Panicum maximum	Poor	Good	Fair	900
	Panicum purpureum	Fair	Good	Fair	1000
Legumes	*Centrosema pubescens*	Poor	Good	Fair	1250
	Desmodium uncinatum	Fair	Fair	Fair	900
	Desmodium heterophyllum	Poor	Fair	Good	1500
	Lablab purpureus	Fair	Good	Poor	500
	Leucaena leucocephala	Fair	Excellent	Poor	500
	Pueraria phaseoloides	Poor	Poor	Good	1000
	Stylosanthes guianensis	Fair	Good	Fair	700
	Stylosanthes humilis	Poor	Excellent	Fair	500

Source: Compiled from Rotar, P.P. and Kretschmer, A.E., Jr., Tropical and subtropical forages, in *Forages; The Science of Grassland Agriculture*, Heath, M.E. and Metcalfe, D.S. (eds.), Iowa State University Press, Ames, IA, 154–165, 1985.

TABLE 18.4
Grass and Legume Species Adapted to Various Soil pH Ranges

Grasses		
pH < 4.5	Weeping lovegrass	*Eragrostis curvula* (Schrad) Nees.
	Bermudgrass	*Cynodon dactylon* L. Pers.
	Switchgrass	*Panicum virgatum* L.
	Bentgrass	*Agrostis canina* L. spp.
	Deertongue	*Panicum clandestinum* L.
	Redtop	*Agrostis alba* L.
	Chewing fescue	*Festuca rubra* var. commutata Gaud.
	Red fescue	*Festuca rubra* L.
	Broomsedge	*Andropogon virginicus* L.
pH 5–6	Orchardgrass	*Dactylis glomerata* L.
	Tall fescue	*Festuca arundinacea* Schreb.
	Bromegrass	*Bromus inermis* Leyss
	Ryegrass	*Lolium perenne* L.
	Timothy	*Phleum pratense* L.
	Little bluestem	*Andropogon scoparius* Michx.
	Kentucky bluegrass	*Poa pratensis* L.
	Reed canarygrass	*Phalaris arundinacea* L.
	Tall oatgrass	*Avena sativa* L.
Legumes		
pH 4–5	Birdsfoot trefoil	*Lotus corniculatus* L.
	Lespedeza species	*Lespedeza cuneata* (Dumont)
	Crownvetch	*Coronilla varia* L.
	Flatpea	*Lathyrus sylvestris* L.
	White clover	*Trifolium repens* L.
	Kura clover	*Trifolium ambiguum* Bieb
	Zigzag clover	*Trifolium medium* L.
pH > 5	White clover	*Trifolium repens* L.
	Crimson clover	*Trifolium incarnatum* L.
	Red clover	*Trifolium pratense* L.
	Alfalfa	*Medicago sativa* L.

Source: Bennett, O.L. et al., Selection and evaluation of forage plant genotypes for low pH and high aluminium tolerance, in *European Grassland*, Borba, F.M. and Abreu, J.M. (eds.), Troia, Portugal, 176–183, 1986.

There was a quadratic response of forage grasses to increasing soil pH from 3 to 6 (Figure 18.2). Similarly, maximum productivity calculated on the basis of regression equation was obtained at a base saturation of about 50% (Figure 18.3). This means that dry matter yields of forage grasses (as well as some legume forages) can be improved by liming.

Scientists at the International Center for Tropical Agriculture (CIAT), Colombia have evaluated forage species for tolerance to soil acidity at sites in tropical America representing the major ecosystems where Ultisols or Oxisols predominate (i.e., the isohyperthermic savannas of Colombia and Venezuela, the isothermic savannas of the Brazilian Cerrado) (Miles and Lapointe, 1992). Several of the identified tropical grasses and legume species produce good yields on acid soils (Table 18.5). A liming trial conducted at CIAT (1980) revealed differences in dry matter yields of tropical legumes at several liming levels (Table 18.6). Some species responded positively to liming, while others showed no response at all.

Salt tolerance of forage grasses and legumes also varies considerably among species, from susceptible to tolerant. Salt tolerance ratings of selected forage grasses and legumes are given in Table 18.7.

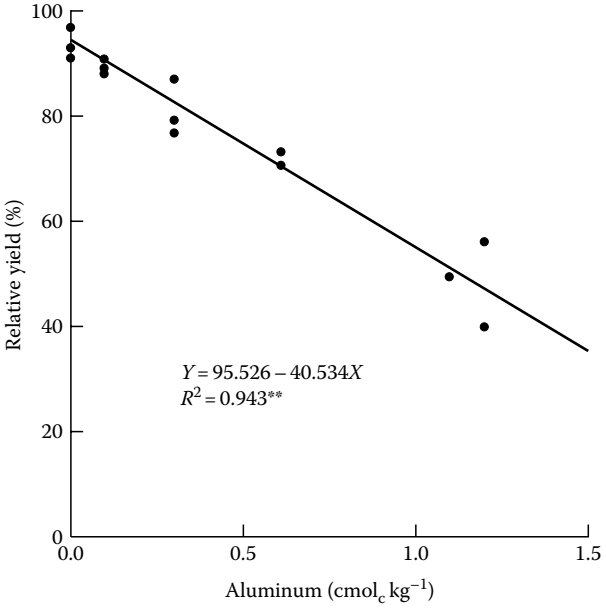

FIGURE 18.1 Effect of soil aluminum on relative dry matter yield of three forage grasses (*Brachiaria brizantha*, *Andropogon gayanus*, and *Panicum maximum*). (From Cruz, M. et al., *Pesq. Agropec. Bras. Brasilia*, 29, 1303, 1994.)

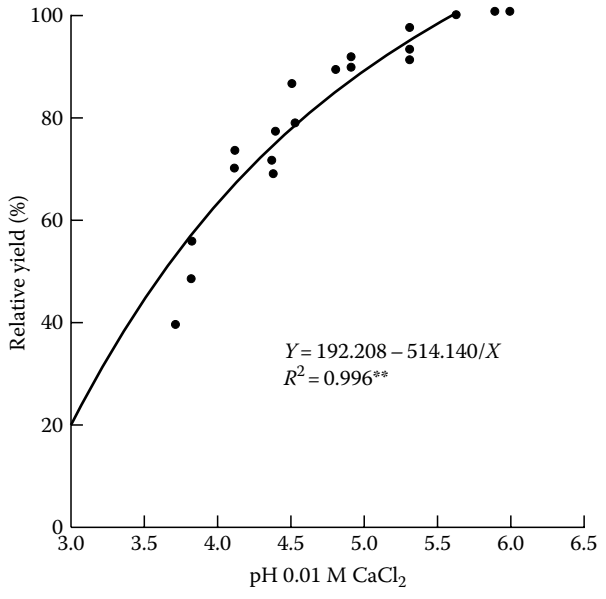

FIGURE 18.2 Relationship between soil pH and relative dry matter yield of three forage grasses (*Brachiaria brizantha*, *Andropogon gayanus*, and *Panicum maximum*). (From Cruz, M. et al., *Pesq. Agropec. Bras. Brasilia*, 29, 1303, 1994.)

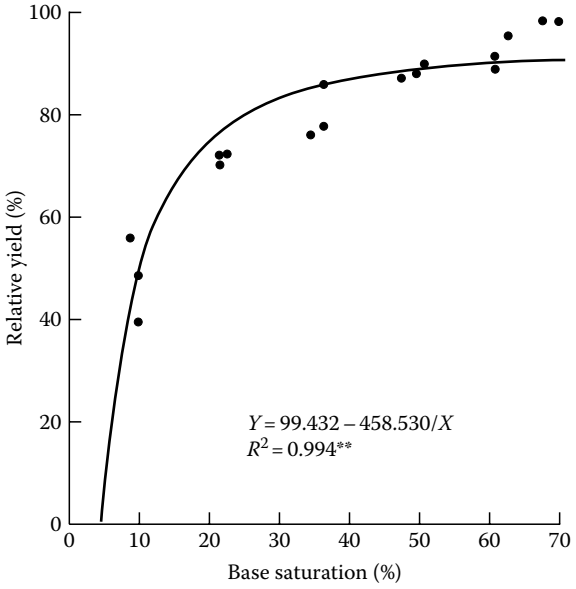

FIGURE 18.3 Relationship between base saturation and relative dry matter yield of three forage grasses (*Brachiaria brizantha*, *Andropogon gayanus*, and *Panicum maximum*). (From Cruz, M. et al., *Pesq. Agropec. Bras. Brasilia*, 29, 1303, 1994.)

TABLE 18.5
Tropical Forage Species with Special Potential on Acid Soils

Grasses	Legumes
Andropogon gayanus	*Arachis pintoi*
Brachiaria brizantha	*Calopogonium mucunoides*
Brachiaria decumbens	*Centrosema acutifolium*
Brachiaria dictyoneura	*Centrosema brasilianum*
Brachiaria humidicola	*Centrosema macrocarpum*
Panicum maximum	*Centrosema pubescens*
	Cratylia arquentea
	Desmodium ovalifolium
	Flemingia macrophylla
	Pueraria phaseoloides
	Stylosanthes capitata
	Stylosanthes guianensis

Source: Zeigler, R.S. et al., Advances in the selection and breeding of acid-tolerant plants: Rice, maize, sorghum and tropical forages, in *Plant–Soil Interactions at Low pH: Principles and Management*, Date, R.A. et al. (eds.), Kluwer Academic Publishers, Dordrecht, the Netherlands, 391–406, 1995.

TABLE 18.6
Effect of Lime on Dry Matter Yields (kg ha^{-1}) of Tropical Legumes, First Cutting

	Lime (Mg ha^{-1})			
Species	**0**	**0.5**	**2**	**6**
Centrosema plumieri CIAT 470	0	0	582	1698
Centrosema sp. CIAT 1787	445	912	2014	2769
Centrosema sp. 1733	356	1330	1568	1317
Centrosema pubescens	680	1729	1996	2035
Desmodium ovalifolium	1118	2302	2018	2480
Pueraria phaseoloides	1286	1688	1422	1434
Zornia sp. CIAT 728	3000	3108	2686	2628
Stylosanthes capitata CIAT 1019	2365	2361	3011	2458

Source: CIAT (Centro Internacional de Agricultura Tropical), Tropical pasture programs, Annual Report 1979, Cali, Colombia, 1980.

TABLE 18.7
Salinity Threshold and Salt Tolerance Rating of Selected Forage Grasses and Legumes

Species		**Salinity Threshold**	**Salinity Rating**[a]
Grasses	Bermudagrass	6.9	T
	Buffelgrass	—	MS
	Italian ryegrass	—	MT
	Reed canarygrass	—	MT
	Dallisgrass	—	MS
	Hardigrass	4.6	MT
	Kallagrass	—	T
	Lovegrass	2.0	MS
	Orchardgrass	1.5	MS
	Panicgrass	—	MT
	Perennial ryegrass	5.6	MT
	Rescuegrass	—	MT
	Rhodegrass	—	MS
	Sudangrass	2.8	MT
	Tall fescue	3.9	MT
	Timothy	—	MS
	Wheatgrass	3.5	MT
Legumes	Alfalfa	2.0	MS
	Common vetch	3.0	MS
	Ladino clover	1.5	MS
	Red clover	1.5	MS
	Sweet clover	—	MT
	White clover	—	MS

Source: Compiled from Maas, E.V., *Appl. Agric. Res.*, 1, 12, 1986.

[a] T, Tolerant; MT, moderately tolerant; MS, moderately susceptible.

18.2 GROWTH AND DEVELOPMENT

Knowledge of morphological development of forage crops can be used to determine the optimum harvest date and predict forage quality and grazing readiness of grasses and legumes (Frank, 1991; Mitchell et al., 2001; Smart et al., 2001). Similarly, understanding the relationship between dry matter partitioning and the nutritive value of leaf and stem components of grasses and legumes during the growing season is important for grazing management decisions (Smart et al., 2006). Moore et al. (1991) quantified the morphological development of perennial grasses by means of an index with constant incremental changes among substages, allowing evaluation of grass sward maturity based on a population rather than a few tillers. This system has been recommended by ASA, CSSA, and SSSA (Frank and Cardwell, 1997). Fick et al. (1994) proposed that this system could be used to predict forage quality for species in which development stage and quality respond to the environment in the same way.

Most forage species are either grasses or legumes, belonging to the families Gramineae and Leguminosae, respectively. Brief descriptions of growth and development of these two types of forage are given in this section.

18.2.1 Grasses

Most grasses are herbaceous annuals or perennials composed of leaves, stems, roots, and inflorescences and are vary widely in size, shape, and growth habit.

18.2.1.1 Roots

Grasses have fibrous root systems. The grass root system may be divided into seminal roots, subcoleoptile internode roots, adventitious roots, and the primary root system (Figure 18.4). Seminal roots are produced from the embryo. The adventitious root system of an established grass plant develops from the coleoptilar node and other nodes above the seed node. Coleoptile length and the

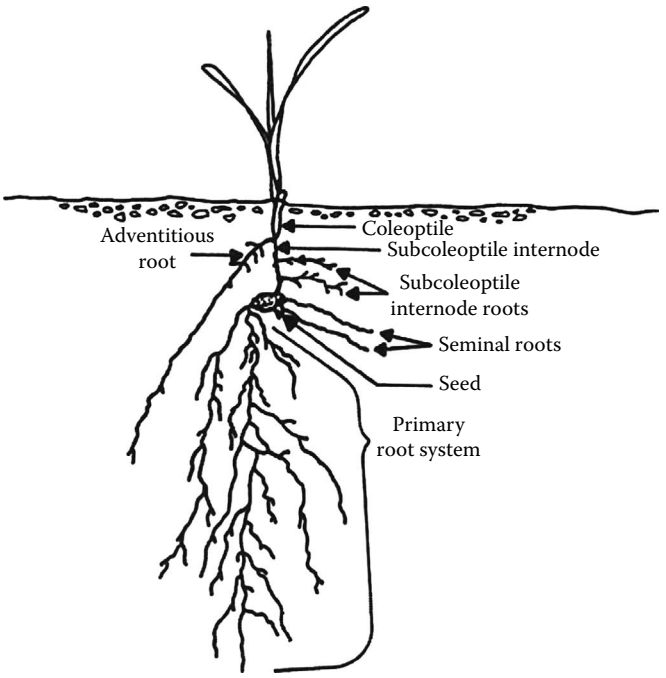

FIGURE 18.4 Grass seedling root system. (From Newman, P.R. and Moser, L.E., *Agron. J.*, 80, 383, 1988. With permission.)

amount of internode elongation between the seed node and coleoptilar node (subcoleoptile internode elongation) determine the position of the seedling crown, which is the source of adventitious roots (Newman and Moser, 1988).

Grass stolons and rhizomes (see discussion below) produce roots at the nodes (Purseglove, 1985), and grasses generally have longer, thinner, more finely branched roots than legumes. These characteristics give grasses a strong competitive advantage over legumes when nutrients and water are in short supply.

18.2.1.2 Stems

The stems of a grass plant (also called culms) are distinctly divided into nodes and internodes. The node or joint is always solid, whereas the internodes may be hollow, pithy, or solid. In addition to the vertical flowering stems or culms, many grasses have horizontal underground stems called rhizomes and creeping stems above the ground called stolons (Metcalfe, 1982). Examples of grasses having rhizomes are Johnsongrass, Kentucky bluegrass, quackgrass, and many others. Two of the best known stoloniferous grasses are buffalograss and bermudagrass. Lateral buds arise in the axils of the leaves, and the leaves have their vascular connections with the stem at the nodes.

18.2.1.3 Leaves

The leaves consist of the sheath, the ligule, and the leaf blade. They are borne on the stem, alternately in two rows, one at each node. The blades are parallel-veined and typically flat, narrow, and sessile.

18.2.1.4 Inflorescence

The inflorescence is usually terminal on the culm and consists of groups or clusters of spikelets arranged in dense to loose panicles. The panicle is the most common type of grass inflorescence. The panicle may be either open, diffuse, or contracted (Metcalfe, 1982). The fruit of most grasses is a caryopsis or kernel.

18.2.2 Legumes

Forage legumes may be annual, biennial, or perennial. A brief description of their roots, stems, leaves, and inflorescences is given below.

18.2.2.1 Roots

Most legumes have a taproot that emerges from a rather narrow protruding crown and penetrates vertically into the ground, with branch roots arising at intervals from it. Such plants are unable to spread laterally like rhizomatous and stoloniferous forage grasses, except to a very limited degree by crown expansion as the plant ages (Heinrichs, 1963). The roots of many forage legumines become infected with *Rhizobium* bacteria that induce formation of N-fixing nodules on the roots. This N-fixation is extremely important as a source of protein in legume–based grazing systems.

18.2.2.2 Tops

The tops of legumes consist of a main stem with axillary branches, usually with compound leaves. A characteristic feature of the legume family is the presence of a pulvinus, a cushionlike structure at the base of the leaflets and of the petiole. Flowers usually are arranged in racemes as in peas, in heads as in clover, or in a spikelike raceme as in alfalfa (Metcalfe, 1982). The fruit is a pod containing one to several seeds. Each seed is enclosed in a testa or seed coat.

18.2.3 Growth Stages

Table 18.8 describes growth stages of grasses and legumes.

TABLE 18.8
Growth Stages in Grasses and Legumes[a]

Growth Stage			Description
Grasses	First growth	Vegetative	Leaves only, stems not elongated. (Specify extended leaf length and if seedling or older plants.)
		Stem elongation	Stems elongated. (Specify early or late jointing depending on less than or more than one-half the leaves exposed, respectively.)
		Boot	Inflorescence enclosed in flag leaf sheath and not showing.
		Heading	Inflorescence emerging or emerged from flag leaf sheath but not shedding pollen. (Specify proportion emerged.)
		Anthesis	Flowering stage, anthers shedding pollen. (Specify if early or late anthesis.)
		Milk stage	Seeds immature, endosperm milky. (Specify if early or late milk.)
		Dough stage	Well-developed seeds, endosperm doughy. (Specify if early or late dough.)
		Ripe seed	Seeds ripe, leaves green to yellow brown.
		Postripe seed	Seeds postripe, some dead leaves and some heads shattered. (Specify amount of dead leaf tissue.)
		Stem cured	Leaves cured on stem, seeds mostly cast. (Specify if frosted.)
	Regrowth[b]	Vegetative	Leaves only, stems not elongated. (Specify extended leaf length.)
		Jointing	Green leaves and elongated stems. (Specify if before or after killing frost.)
		Late growth	Leaves and stems weathered. (State age of growth and time of year; specify if before or after killing frost.)
Legumes[c]	Spring and summer growth	Vegetative (or prebud)	No buds. (Specify plant height and if seedling or older plants.)
		Bud	No flowers. (Specify early or late bud based on condition of the floral buds.)
		First flower	First flowers appear on plants.
		Bloom (flower)	Plants flowering. (Specify percent of stems with one or more flowers; determine from 100 randomly selected stems.)
		Pod (or green seed) development	Green seedpods developing. (Specify percent of stems with one or more green seedpods formed; estimate amount of leaf loss, if any.)
		Ripe seed	Mostly mature brown seedpods with lower leaves dead and some leaf loss. (Estimate amount of leaf loss.)
	Fall recovery growth		Vegetative or with floral development. (Specify plant height and condition of floral development.)

Source: Reprinted from Metcalfe, D.S., The botany of grasses and legumes, in *Forages: The Science of Grassland Agriculture*, 3rd edn, Heath, M.E. et al. (eds.), Iowa State University Press, Ames, IA, 80–97, 1982.

[a] Specify date of observation, cutting number, days of regrowth, and species and cultivar. Dry matter percentage and extended leaf growth measurements are recommended at all growth stages.

[b] If flowering occurs, use nomenclature outlined for first-growth forage.

[c] These growth stages best describe upright-growing legumes. For stoloniferous legumes like white clover, specify if leaves and floral stems only are included or if stolons are also.

18.2.4 Stand Establishment

Many forage species, both grasses and legumes, have small seeds with poor seedling vigor, little drought tolerance, and an inability to withstand weed competition. As a result, forage establishment is often a significant problem. Cultivars of some forage species such as hybrid bermudagrass (*Cynodon dactylon* L. Pers.) are established vegetatively from rhizomes or stolons, a more expensive but less risky method. In addition, some stand establishment systems use annual species as nurse crops to suppress weed competition while the less vigorous forage seedlings become established. For example, in Brazil, scientists at the National Rice and Bean Research Center of the Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA) have developed a technology of improving degraded pastures on cleared rainforest lands by planting upland rice in association with *Brachiaria brizanta*. Approximately 5 kg of *Brachiaria* seeds are mixed with fertilizers and placed 8–10 cm deep, with upland rice sown at about 3–5 cm. The grass germination is delayed, and in this way rice escapes from competition with grass. When the rice is mature, it is harvested, and the *Brachiaria* recovers and is ready to graze within about 60–70 days. In this way, the farmers can get extra income from upland rice and at the same time establish pastures for animal production (Kluthcouski et al., 1991).

18.2.5 Growth Habits

The growth habit of pasture species is an extremely important characteristic because it governs the response of plants to defoliation. The proportion of tops of pasture species removed by grazing animals varies according to the plants' growth habit. The grazing animal removes a greater proportion of tops of upright plants than of plants of prostrate growth habit and hence, in the latter case, relatively more green leaf, stem, and sheath is left after grazing to facilitate regrowth (Haynes, 1980). Figure 18.5 shows the growth habit of upright and prostrate grasses and legumes and the relative amount of tops remaining after defoliation. Forage species with upright growth habits are more susceptible to damage by grazing than those with a prostrate or creeping growth habit. Growth habit is also important in competition of forage species in pastures. Red clover has an upright growth habit and has an immediate advantage over prostrate white clover whenever the grazing interval is long enough to allow the grasses to shade the clovers. However, because of its prostrate habit, in comparison with red clover, white clover is able to recover very quickly from cutting or grazing (Haynes, 1980).

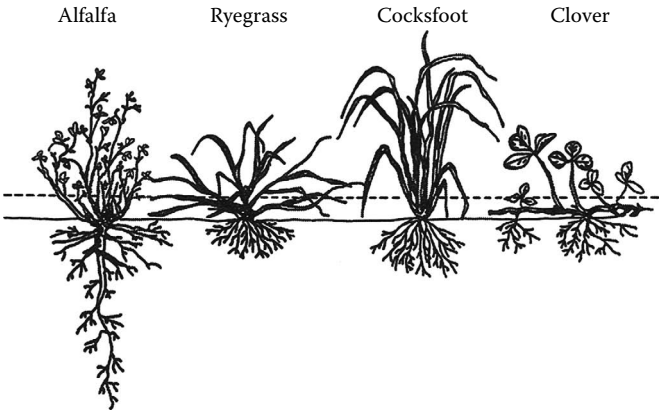

FIGURE 18.5 Growth habits of upright and prostrate legumes and grasses and their influence on the relative amount of shoot material left after defoliation. Dotted line represents height of defoliation. (Reproduced from Haynes, R.J., *Adv. Agron.*, 33, 227, 1980. With permission.)

TABLE 18.9
Selected Forage Grasses and Legumes with High and Low Photosynthetic Capacity

Species	High Photosynthetic	Low Photosynthetic
Grasses	*Andropogon scoparium* Michx.	*Agropyron repens* (L.) Beauv.
	Andropogon virginicus L.	*Agrostis alba* (L.)
	Cenchrus ciliaris L.	*Dactylis glomerata* L.
	Cynodon dactylon (L.) Pers.	*Festuca arundinacea* Schreb.
	Cyperus rotundus L.	*Lolium multiflorum* Lam
	Cyperus esculentus L.	*Panicum commutatum* Schult.
	Digitaria pentzel Stent.	*Phalaris arundinacea* L.
	Eragrostis chloromelas Strud.	*Phalaris canariensis* L.
	Panicum capillaare L.	*Poa pratensis* L.
	Panicum maximum Jacq.	
	Panicum virgatum L.	
	Paspalum dilatatum Poir.	
Legumes	*Atriplex rosea* L.	*Cassia tora* L.
	Atriplex semibaccata R.Br.	*Crotalaria spectabilis* Roth.
	Atriplex spongiosa F.V.M.	*Pueraria lobata* (Wild.) Ohwi.
		Vicia sativa L.

Source: Compiled from Black, C.C., *Adv. Ecol. Res*., 7, 87, 1971.

18.2.6 Dry Matter

Dry matter production of forage grasses and legumes depends on photosynthetic efficiency, which is determined by plant species, temperature, nutrient and water supply, solar radiation, and management practices. Perennial tropical grasses and legumes have the potential for year-round production of herbage.

Leaf area index (LAI), defined as the ratio of leaf surface area to soil surface area, is one of the most important growth parameters in dry matter production in forages. The optimum LAI for maximum growth varies greatly with species. It is reported that optimum LAI for *Panicum maximum* and *Cynodon dactylon* is about 4 (Alexander and McCloud, 1962; Humphreys, 1966). Similarly, the optimum LAI for white and red clovers was reported to be in the range of 3–5, and for ryegrasses from 5 to 6 (Brougham, 1960). Forage grasses and legumes have different photosynthetic production capacities due to differences in plant anatomy, plant physiology, and plant biochemistry (Black, 1971). Genotypic variation for growth rate has also been found among forage species (Wilson, 1975, 1982). Table 18.9 shows forage grasses and legumes with high and low photosynthetic capacity. Table 18.10 shows the dry matter production of some forage grasses and legumes in different countries.

18.3 GRASS–LEGUME MIXTURES

Many improved pasture systems consist of grass–legume mixtures rather than a monoculture. The grasses are expected to provide the bulk of the energy to cattle because of their larger dry matter production. The role of legumes in such mixtures is to supply N to the grasses and improve the overall nutritional content of the forage, particularly that of protein, phosphorus, and calcium (Sanchez, 1976; Exner and Cruse, 2001). Use of a cereal grain companion crop is the most common legume establishment method in the North Central United States, and this method has been used historically to establish 85% of the alfalfa fields in Iowa (Tesar and Marble, 1988; Blaser et al., 2006).

TABLE 18.10
Dry Matter Production of Selected Forage Species in Different Countries

Species	Country	Growth Duration (days)	Growth Rate (g m^{-2} day^{-1})	Dry Matter (t ha^{-1})
Digitaria decumbens Stent.	Cuba—23°N	365	10.8	39.4
Digitaria decumbens Stent.	Australia—27°N	365	6.6	24.4
Lolium perenne L.	England—52°N	365	7.9	29.0
Lolium perenne L.	New Zealand—40°S	365	7.3	26.6
Medicago sativa L.	United States—38°S	250	13.0	32.5
Pennesetum purpureum Schumach.	El Salvador—14°N	365	23.2	85.2
Panicum maximum Jacq.	Puerto Rico—18°N	365	13.4	48.8
Panicum maximum Jacq.	Nigeria—7°N	328	7.1	23.4
Panicum clandestinum Hochst.	Australia—27°S	365	8.2	30.0
Stylonsanthes guyanensis (Aubl.) Scv.	Ghana—7°N	365	5.8	21.1
Trifolium pratense L.	New Zealand—40°S	365	7.2	26.4

Sources: Compiled from Eagles, C.F. and Wilson, D., Photosynthetic efficiency and plant productivity, in *Handbook of Agricultural Productivity*, Recheigl, M., Jr. (ed.), CRC Press, Boca Raton, FL, 213–247, 1982; Rodrigues, L.R.A. and Rodrigues, T.J.D., Ecofisologia de plantas forrageiras, in *Ecofisologia da Producao Agricola,* Castro, P.R.C. et al. (eds.), Associacao Brasileira para pesquisa da Potassa e do Fosfato, Piracicaba, Brazil, 203–230, 1987.

Legumes grown in combination with cool-season grasses can provide symbiotic N to associated grass (Farnham and George, 1993; Gettle et al., 1996) and improve total yields (George, 1984). Legumes have also been successfully grown with warm-season grasses in the southern United States to extend the growing season (Evers, 1985). Brown and Byrd (1990) reported that the yield of an alfalfa-bermudagrass [*Medicago sativa* L.-*Cynodon dactylon* (L.) Pers.] mixture was similar to bermudagrass fertilized with 100–300 kg N ha^{-1} in Georgia. Haby et al. (2006) also reported that growing alfalfa with bermudagrass may reduce the N fertilizer requirement of the grass. Alfalfa derived 93%–95% of its N symbiotically when grown with reed canarygrass (*Phalaris arundinacea* L.) (Brophy et al., 1987; Heichel and Henjum, 1991), 80%–85% of its N from the atmosphere when grown in a mixed stand with annual ryegrass (*Lolium multiflorum* Lam.) (Danso et al., 1988), and 91% of its N from atmospheric N fixation when grown in mixed stand with orchardgrass (*Dactylis glomerata* L.) (West and Wedin, 1985). Posler et al. (1993) observed greater yields in Kansas with five of six native, legume-switchgrass mixtures compared with unfertilized switchgrass. Turner et al. (2006) reported that dryland dairy areas of southern Australia may benefit from the introduction of alternative grass species such as prairie grass (*Bromus willdenowii* Kunth.) when used in combination with perennial legumes such as white clover (*Trifolium repens* L.).

It is important to note that not all grass–legume associations are successful. For example, Marten (1989) suggested that warm-season grasses may be incompatible with cool-season legumes because of differences in growth habit, relative maturity, harvest schedules, and poor persistence. Taylor and Jones (1983) observed that alfalfa and red clover were not compatible with switchgrass grown in Kentucky, regardless of cutting management. In this same study, however, bigflower vetch (*Vicia grandiflora* Scop.) persisted well with switchgrass, with the mixture containing 20% legume and yielding 9.4 Mg ha^{-1}.

Grass–legume mixtures improved soil aggregate size and water infiltration (Table 18.11). This means better environment for grasses as well as legumes and higher dry matter yield. The addition of legumes with grasses also improved soil biological activity. Data in Table 18.12 show that, compared with native savanna, the biological activity of the improved pastures, in terms of the population of nitrifying bacteria and mycorrhizal spores and percent of mycorrhizal root infection,

TABLE 18.11
Soil Physical Properties in Different Pastures in a Medium-Texture Oxisol of Carimagua, Colombia

Pastures	% of Soil Aggregates >0.5 mm	Water Sorptivity (cm $s^{-1/2}$)
Native savanna	9.6a	0.20a
Improved grass	25.5b	0.40b
Grass–legume pasture	31.9b	0.39b

Source: Rao, I.M. et al., *Pastures for the Tropical Lowlands: CIAT's Contribution*, CIAT, Cali, Colombia, 1992.
Means in a column not followed by the same letter differ at 5% probability level.

TABLE 18.12
Comparison of Soil Biological Activity in Different Pastures

Soil Biological Characteristic	Savanna	Improved Grass	Grass + Legume
Nitrifying bacteria (number/g soil)	3.9×10^6	2.7×10^8	—
VA mycorrhizal fungi spore population (spores/100 g soil)	50	190	275
Root infection with VA mycorrhizae (%)	31	54	58
Earthworm activity (casts/m^2)	0.9	2.1	3.1

Source: Rao, I.M. et al., Soil-plant factors and processes affecting productivity in ley farming, in *Pastures for the Tropical Lowlands: CIAT's Contribution*, CIAT (ed.), CIAT, Cali, Colombia, 145–175, 1992.

was markedly higher. The activity of earthworms also increased threefold in the improved pastures. This increased biological activity is beneficial to soil properties such as mineralization, humification, texture, porosity, and water infiltration and retention. Soil characteristics are both a determinant and the consequence of earthworm activities, since these macroorganisms greatly influence the functioning of the soil system. They build and maintain the soil structure and take an active part in energy and nutrient cycling through the selective activation of both mineralization and humification processes (Lavelle, 1988).

The contribution of legume residues to soil organic matter quality and turnover together with improved soil fertility, soil structure, and biological activity were associated with a 1.7 Mg ha^{-1} yield increase in a rice crop following 10 year old grass + legume plots. In addition, the grass + legume plots did not require any fertilizer N when compared with rice following a grass-alone pasture of the same age (Rao et al., 1992). Further, grass–legume mixtures improve distribution of crop production through time, reduce forage susceptibility to disease and lodging, and produce more nutritionally balanced forage for livestock (Cruz and Sinoquet, 1994; Thomas and Sumberg, 1995).

Botanically stable and productive grass–legume forage mixtures are often difficult to maintain because of the high degree of competition among their components (Jones et al., 1988). Grasses and legumes may compete for solar radiation, water, and nutrients when grown in mixture. Competition for solar radiation is often considered the most critical of these requirements (Donald, 1961); however, competition for nutrients and water are also important.

The legumes grass–legume forage mixtures normally have lower water-use efficiencies than the associated grasses; therefore, grasses often have a competitive advantage in water-limiting environments. However, the tap root system of the legume may be able to extract water from deeper in the

soil profile than the grass, giving the legume an advantage in long dry periods (Chamblee, 1972; Snaydon, 1978; Haynes, 1980).

Grasses have fibrous root systems and are generally concentrated in the top soil layers, whereas legumes have taproot systems and penetrate deeper into the soil. The fibrous nature of grass roots give grasses an advantage over legumes in extracting mobile monovalent cations from the soil (Haynes, 1980). In addition, grass roots have more root hairs than legumes, and the effective root surface area for nutrient absorption is reported to be three to eight times higher in grasses than in legumes (Barrow, 1975; Evans, 1977). Thus, it is likely that direct competition for phosphate ions occurs in the top soil, with grasses having a physical advantage over legumes. As a result, in soils deficient in P, legumes are likely to undergo considerable P stress in mixtures with grasses (Kendall and Stringer, 1985), and application of relatively immobile nutrients like P, K, or S is generally more beneficial to legumes than to the grass components of grass–legume mixtures (Haynes, 1980).

The compatibility of grass and legume species is related to their abundance in the mixture. For example, as a general rule, the optimum ratio of tall fescue to white clover in the sward is considered to be 2:1 (Leffel and Gibson, 1982). However, the ability of forage grasses and legumes to form successful mixtures also depends on their growth habits, their responses to climate, soil moisture, soil fertility, and defoliation (Sanchez, 1976). Thus, it is important to select the proper grass and legume species for a given environment and set of management practices. Table 18.13 shows some

TABLE 18.13
Some Examples of Successful Grass–Legume Mixtures in Different Countries

Country	Grass Species	Legume Species
Australia	*Brachiaria mutica*	*Centrosema pubescens*
	Setaria sphacelata	*Desmodium intortum*
	Sorghum almun	*Medicago sativa*
Columbia	*Melinis minutiflora*	*Stylosanthes guyanensis*
Kenya	*Pennisetum clandestinum*	*Desmodium uncinatum*
Peru	*Panicum maximum*	*Pueraria phaseoloides*
United States	*Dactylis glomerata*	*Medicago sativa*
	Bromus inermis	*Medicago sativa*
	Phleum pratense	*Medicago sativa*
	Hemarthria altissima	*Aeschynomene americana*
Brazil	*Panicum maximum*	*Centrosema pubescens*
	Panicum maximum	*Pueraria phaseoloides*
	Brachiaria decumbens	*Centrosema pubsecens*
New Zealand	*Lolium perenne*	*Trifolium repens*

Sources: Compiled from Janick, J. et al., *Plant Science: An Introduction to World Crops*, Freeman, San Francisco, CA, 1969; Sanchez, P.A., Soil management for tropical pasture production, in *Properties and Management of Soils in the Tropics*, Wiley, New York, 533–605, 1976; Hutton, E.M., Problems and successes of legume–grass pastures, especially in tropical Latin America, in *Pasture Production in Acid Soils of the Tropics*, Sanchez, P.A. and Fergas, L.E. (eds.), CIAT, Cali, Colombia, 81–93, 1978; Kornelius, E. et al., Pastures establishment and management in the cerrado, in *Pasture Production in Acid Soils of the Tropics*, Sanchez, P.A. and Fergas, L.E. (eds.), CIAT, Cali, Colombia, 147–166, 1978; Haynes, R.J., *Adv. Agron*., 33, 227, 1980; Sollenberger, L.E. et al., *Agron. J.,* 79, 1049, 1987; Casler, M.D., *Agron. J*., 80, 509, 1988.

examples of successful grass–legume mixtures in Colombia, Brazil, Peru, Kenya, Australia, the United States, and New Zealand.

In many cases, grasses tend to dominate the grass–legume mixture, both because of the grasses' advantages in capturing light, water, and nutrients and because of selective grazing of more protein-rich legume forage. As a result, it may be necessary to implement management practices that favor the legume (Janick et al., 1969). These may include (1) close grazing (or mowing); (2) rotational grazing, which provides a recovery period; (3) mowing and weed control of grass patches that become undergrazed; (4) making hay if growth exceeds the livestock's capacity to consume excess grass; (5) using fertilizers rich in phosphate and potassium (legumes provide much of their own nitrogen); and (6) suppressing grass competition by physical or chemical means.

18.4 NUTRITIVE VALUE

The nutritive value of a forage depends on its chemical composition, digestibility, and the nature of the digested products (Mott, 1982; Belesky et al., 2006; Karn et al., 2006). The most important criteria used to evaluate forage nutritive values are dry matter digestibility (DMD) and forage intake. Digestibility can be defined as the difference between dry matter of feed eaten and material voided by the animals, expressed as a percentage of the feed eaten (Crowder and Chheda, 1982). The dry matter digestibility can be calculated as follows:

$$\text{DMD } (\%) = \frac{100(\text{DM eaten} - \text{DM in feces})}{\text{DM eaten}}$$

The voluntary intake (VI) is defined as the amount eaten in relation to the size of the animal.

Soil fertility level, season, growth stage, genotype and species, and management practices affect the nutritive value of forages (Reid et al., 1970; Karn et al., 2006). The physiological processes of nutrient absorption, photosynthesis, and translocation do not proceed at similar rates throughout the growing season. Nitrogen, phosphorous, and potassium are absorbed most actively in the earlier stages of plant growth, while photosynthesis and dry matter accumulation reach their maxima much later. As a consequence, the protein, phosphorus, and potassium concentrations of most forages decrease as the plant matures (Trumble, 1952). This is particularly marked in the case of grasses, in which nutritive value declines after stem elongation and the appearance of inflorescences (Berg and Hill, 1989; Cherney et al., 1993). In contrast, legumes often have their highest feeding value later in the growth cycle (Trumble, 1952). In addition, the nutritive value of hay, which has been cut and is drying in the field, is usually reduced by rainfall, which leaches soluble, nonstructural carbohydrates from the forage (Collins, 1982; Scarbrough et al., 2005).

The nutritive value of pasture species, even at similar stages of growth, varies widely in both DMD and VI. Minson and McLeod (1970) reviewed comparisons of over 1000 tropical and temperate grass samples and showed that tropical grasses were an average of 13% units lower in DMD. Most samples of temperate grasses had digestibilities above 65%, but few tropical grass samples were in that category. They suggested that lower DMD values of tropical grasses may be due in part to higher growing temperatures. But the data of Reid et al. (1973) support the view that for selected or improved species of tropical grasses such as *Brachiaria*, *Chloris*, *Setaria*, and *Panicum*, DMD values are comparable to those of similarly managed temperate grasses. A detailed discussion of nutritive value of forage species is given by Crowder and Chheda (1982) and Van Soest (1982).

TABLE 18.14
Estimated N Fixation by Tropical Pasture Legumes and Transfer to Associated Grasses

Species	N Fixed[a] (kg ha^{-1} year^{-1})	N Transferred[b] to Grasses (%)	Location	Reference
Centrosema mucunoides	90	20	Queensland, Australia Average of 4 years	Miller and Vanderlist (1977)
Centrosema pubescens	100	—	São Paulo, Brazil Average of 3 years	Mattos and Werner (1979)
Desmodium intortum	238	39	Hawaii, USA Average of 2 years	Whitney and Green (1969)
Desmodium intortum	172	20	Queensland, Australia Average of 4 years	Miller and Vanderlist (1977)
Desmodium intortum	100–140	17	Queensland, Australia Average of 5 years	Johansen and Kerridge (1979)
Galactia straita	122	—	São Paulo, Brazil Average of 3 years	Mattos and Werner (1979)
Lotononis bainesii	66	13	Queensland, Australia Average of 4 years	Jones et al. (1967)
Lotononis bainesii	51–74	12–15	Queensland, Australia Average of 5 years	Johansen and Kerridge (1979)
Macroptilium atropurpureum	135	39	Queensland, Australia Average of 4 years	Miller and Vanderlist (1977)
Macroptilium atropurpureum	100–140	12–15	Queensland, Australia Average of 5 years	Johansen and Kerridge (1979)
Macroptilium atropurpureum	85	—	São Paulo, Brazil Average of 3 years	Mattos and Werner (1979)
Neonotonia wightii	133	19	Queensland, Australia Average of 4 years	Miller and Vanderlist (1977)
Neonontonia wightii	40	—	São Paulo, Brazil Average of 2 years	Paulino et al. (1983)
Pueraria phaseoloides	99	14	Queensland, Australia Average of 4 years	Miller and Vanderlist (1977)
Stylosanthes guianensis	135	10	Queensland, Australia Average of 4 years	Miller and Vanderlist (1977)
Stylosanthes quianensis	43	—	São Paulo, Brazil Average of 3 years	Mattos and Werner (1979)

[a] N fixed (NF) = $N_L + N_G^+ - N_G^-$, where N_L = N in legumes, NG^+ = N in grass associated, and N_G^- = N in grass plot without legume.

[b] N transferred (NT) = $N_G^+ - N_G^-$.

TABLE 18.15
***Rhizobium* Species Associated with Nitrogen Fixation in Selected Forage Legumes**

Legume Species	*Rhizobium* Species
Alfalfa	*Rhizobium meliloti*
Clover	*Rhizobium trifolii*
Crotalaria	*Rhizobium japonicum*
Kudzu	*Rhizobium japonicum*
Lathyrus	*Rhizobium leguminosarum*
Lespedeza	*Rhizobium japonicum*
Sweet clover	*Rhizobium meliloti*
Vetch	*Rhizobium leguminosarum*

18.5 NITROGEN FIXATION

The data on nitrogen fixation by forage legumes in grass–legume mixtures are scarce. Most of the data available are for pure stands. This lack of information is unfortunate because, in practice, forage legumes are often planted with grasses or over time become mixed with grasses. According to Larue and Patterson (1981), nitrogen fixation by alfalfa, white clover, red clover, and Korean lespedeza averages 212, 128, 154, and 193 kg N ha^{-1} annually, respectively. Carvalho (1986) compiled data on N fixation by tropical pasture legumes and N transferred to associated grasses. These data are presented in Table 18.14.

Early studies of the *Rhizobium*–legume association revealed that there are many kinds of nodule bacteria and that different legumes preferentially associate with different bacteria (Fred et al., 1932). Table 18.15 shows the *Rhizobium* species that form nodules on the roots of some important forage legumes. Leguminous plants mutually susceptible to nodulation by the same strains of rhizobia constitute a cross-inoculation group. The rhizobia capable of nodulating plants within a group are considered a species (Burton, 1972). According to Burton (1972), the ability of rhizobia to induce nodulation is called infectiveness; N-fixing capacity indicates effectiveness. While nodulation is a prerequisite of growth enhancement, it does not assure it. Effects attributable to rhizobia are termed strain variation; those attributable to the plants are referred to as host specificity (Burton, 1972).

Nodulation of legumes requires infection of the legume roots by infective bacteria living in the soil or supplied in inoculum applied to the legume seed. Normally, legume seeds are inoculated because of the ease and convenience of this method of placing rhizobia in the rhizosphere. The number of rhizobia required for effective nodulation varies with seeds, form of inoculum, and environmental conditions. In Austria, inocula that provide 100 viable rhizobia per seed are considered satisfactory under normal conditions (Vincent, 1968). In New Zealand, inoculants supply approximately 1000 rhizobia per seed, whereas quality inoculants in the United States provide approximately 5000 rhizobia per alfalfa seed (Burton, 1972). The inoculants available for inoculation of legume seeds are as powder, liquid, or an oil-dried preparation absorbed in pulverized vermiculite. Seeds can be inoculated by sprinkle, slurry, or waterless methods.

18.6 NUTRIENT REQUIREMENTS

Nutrient requirements of forage species vary with yield levels, species, soils, and climatic conditions. In many parts of the world, forages are grown on land that is not suitable for grain crops. These soils may be steep, erodible, infertile, or droughty. Forage grasses are able to thrive on such

soils and respond favorably to good management practices. Fertilization and/or irrigation of pastures can greatly improve forage production in many parts of the world.

Several metabolic disorders in cattle have been related to mineral imbalances in the forages they consume (Noller and Rhykerd, 1974; Reid and Jung, 1974). Most agronomists and plant breeders have concentrated on maximizing forage yield, digestibility, and persistence but have invested little effort in improving mineral concentrations of forages with respect to animal requirements. Management practices and cultivars that maximize yields have contributed to mineral imbalances in animals because mineral requirements of plants and animals differ (Reid and Jung, 1974). Diet supplementation, choice of species, alternation of fertilizer application, and breeding for specific mineral concentrations are methods of correcting imbalances in livestock diets (Hill and Jung, 1975).

Grass tetany, a conditioned Mg deficiency, is a serious nutritional problem in various parts of the United States (Rendig and Grunes, 1979; Kubota et al., 1980). Incidence of tetany is generally reported to be low or absent in areas where grasses have ≥0.2% Mg (Kubota et al., 1980).

Important forage legumes such as alfalfa and clover produce better yields where nutrients like P, K, Ca, and Mg are present in adequate amounts. Similarly, all the important forage grasses require an ample supply of N for high production.

High soil acidity is a known limitation to pasture development in tropical as well as temperate regions around the world (Andrew and Hegarthy, 1969; Recheigl et al., 1988). In acid soils, the major limiting factors include low pH, toxic concentrations of aluminum and/or manganese, and deficiencies of calcium, magnesium, phosphorus, and molybdenum. Liming is considered to be an essential practice in improving pasture production in acid soils. Many soils in areas of permanent grassland in England and Wales are acidic and require liming to achieve optimum production (Jarvis, 1984). Current advisory recommendations are that grassland soils should be limed to pH 6 as measured in a 1:2.5 suspension of soil in water (Jarvis, 1984).

Soil testing, along with plant analysis, helps in formulating sound forage fertilization programs. In order to use soil testing as a criterion for fertilization, field calibration data are required for immobile nutrients and forage species in different agroclimatic regions and grass–legume mixtures.

18.6.1 Nutrient Concentration and Uptake

The basic principle of plant analysis is that the chemical composition of the plant or its parts reflects the adequacy of the nutrient supply in relation to growth requirements (Martin and Matocha, 1973; Fageria and Baligar, 2005; Fageria, 2009), but nutrient supply to a growing plant is influenced by several environmental and plant factors that influence both growth and chemical composition (Adeli et al., 2003; Brink et al., 2003; McLaughlin et al., 2004, 2005). Therefore, although the values of nutrient concentration and nutrient removal presented in this section provide guidelines, they cannot be used for all agroclimatic conditions. Table 18.16 shows adequate levels of nutrients for two legumes and two grasses, and Table 18.17 shows concentrations of P, K, Ca, Mg, and S for tropical pasture species. Similarly, Table 18.18 shows dry matter production and nutrient removal by selected forage species under Brazilian conditions. It can be seen from Table 18.18 that N and K are elements that are removed by forage species in large amounts. This means that these two nutrients should be given special attention in pasture management. In pasture testing, it is extremely important that plant samples be taken at the proper growth stage for chemical analysis. According to Martin and Matocha (1973), alfalfa and clover plant samples should be taken at or near the early bloom stage or at the time when regrowth sprouts begin to appear. This may be true for other forage species also.

Plant demand and uptake of any nutrient is a function of the plant's internal concentrations and its rate of growth. Aluminum is known to interfere with the uptake, transport, and use of several essential elements (Foy, 1984). In many acid soils, aluminum inhibits root growth and mineral

TABLE 18.16
Adequate Nutrient Concentrations in Two Legume and Two Grass Species

	g kg^{-1}						mg kg^{-1}					
Species, Growth Stage, and Plant Part	**N**	**P**	**K**	**Ca**	**Mg**	**S**	**Fe**	**Mn**	**Z**	**Cu**	**B**	**Mo**
Alfalfa, early flowering, whole tops	35–50	2.5–4.0	20–35	10–20	2.5–5.0	2.5–4.0	45–60	25–30	15–40	5–15	25–60	>0.2
White clover, preflowering, whole tops	48–55	3.5–4.0	11–20	>11	1.8–2.2	2.0–3.0	50–65	25–30	16–19	6–7	25–30	0.15–0.20
Perennial ryegrass, preflowering, leaf	25–40	2.0–4.0	15–30	2.5–6.0	2.0–3.5	2.0–4.0	50–60	50–300	15–50	5–12	5–15	0.3–0.4
Bermudagrass, 4–5 weeks, whole tops between clippings	25–30	2.6–3.2	18–21	—	—	1.5–2.0	—	—	—	—	—	—

Sources: Compiled from Martin, W.E. and Matocha, J.E., Plant analysis as an aid in the fertilization of forage crops, in *Soil Testing and Plant Analysis,* Walsh, L.M. and Beaton, J.D. (eds.), Soil Science Society of America, Madison, WI, 393–426, 1973; Smith, F.W., Pasture species, in *Plant Analysis: An Interpretation Manual*, Reuter, D.J. and Robinson, J.B. (eds.), Inkata Press, Melbourne, Australia, 100–119, 1986.

TABLE 18.17
Macronutrient Concentrations of Some Selected Tropical Pasture Species under Brazilian Conditions

		g kg^{-1}				
Species		**P**	**K**	**Ca**	**Mg**	**S**
Grasses	*Panicum maximum*	1.7	11.5	6.0	2.0	1.5
	Hyparrhenia rufa	1.6	10.6	3.4	2.2	1.4
	Andropogon gayanus	1.0	9.5	2.3	1.3	1.3
	Brachiaria brizantha	0.9	8.2	3.7	2.4	1.2
	Brachiaria dictyoneura	1.3	9.8	2.5	2.2	1.2
	Brachiaria decumbens	0.8	8.3	3.7	2.1	1.2
	Brachiaria humidicola	0.8	7.4	2.2	1.6	1.1
Legumes	*Stylosanthes humilis*	2.7	6.0	20.0	2.5	1.4
	Stylosanthes guianensis	1.6	8.2	8.5	3.0	1.4
	Stylosanthes capitata	1.2	11.3	9.7	2.2	1.2
	Stylosanthes macrocephala	1.0	9.3	7.8	2.0	1.4
	Pueraria phaseoloides	2.2	12.2	10.4	2.0	1.7
	Centrosema pubescens	1.8	14.0	9.8	2.4	1.6
	Centrosema macrocarpum	1.6	12.4	7.2	2.2	1.6
	Zornia latifolia	1.2	11.6	8.2	2.0	1.4
	Desmodium ovalifolium	1.0	10.3	7.4	2.1	1.2

Source: Veiga, J.B. and Falesi, I.C., Recomendacao e pratica de adubacao de pastagens cultivados na amazonia brasileira, in *Calagem e Adubacao de Pastagens,* Mattos, H.B. et al. (eds.), Associacao Brasileira para pesquisa de Potassa e do Fosfato, Piracicaba, Brazil, 257–282, 1986.

TABLE 18.18
Dry Matter Production and Corresponding Macronutrients Removed by Selected Forage Species

		kg ha^{-1}					
Species	**Dry Matter (t ha^{-1})**	**N**	**P**	**K**	**Ca**	**Mg**	**S**
Alfalfa	15	335	30	207	40	—	—
Red clover	10	160	20	108	24	—	—
Napiergrass	25	302	64	504	96	63	75
Bermudagrass	25	570	63	308	—	—	—
Pangolagrass	24	299	47	358	109	67	45
Paragrass	24	307	43	383	115	79	—
Colonial grass	23	288	44	363	149	99	45

Source: Malavolta, E. et al., Exigeneias nutriconais das plantas forrageiras, in *Calagem e Adubacao de Pastagens*, Mattos, H.B. et al. (eds.), Associacao Brasileira para pesquisa da Potassa e do Fosfato, Piracicaba, Brazil, 31–76, 1986.

TABLE 18.19
Nutrient Uptake Inhibition in Various Legumes and Grasses by Presence of 100 µm Al in the Growth Medium

	Percent Inhibition of Uptake (PI)[a]					
	Legumes			Grasses		
Element	Alfalfa	Birdsfoot Trefoil	Red Clover	Orchard Grass	Tall Fescue	Timothy
P	98	86	61	88	70	58
K	95	72	–29	73	42	19
Mg	95	84	62	97	88	87
Cu	94	81	96	93	62	58
Fe	96	88	85	92	70	30
Mn	97	87	63	94	68	73
Zn	94	72	51	91	52	50

Sources: Baligar, V.C. et al., *J. Plant Nutr.,* 11, 549 1988; Baligar, V.C. and Smedley, M.D., *J. Plant Nutr*., 12, 783, 1989.

[a] $PI = \left[\frac{\text{Uptake at 0 µM Al} - \text{uptake at 100 µM Al}}{\text{Uptake at 0 µM Al}}\right] \times 100.$

TABLE 18.20
Uptake (U) and Percent Inhibition (PI) of Two Nutrients in Two Red Clover Cultivars at 0, 50, and 100 µM Al Levels

	Altaswede[a]			Kenstar[a]		
	U[b]	PI		U	PI	
Element	0 µM Al	50 µM Al	100 µM Al	0 µM Al	50 µM Al	100 µM Al
P	6.0	70	92	7.0	44	88
S	5.6	61	91	6.5	51	90
K	58.4	51	87	50.3	32	81
Ca	62.5	61	97	84.1	63	96
Mg	8.8	65	94	9.4	56	93
Mn	177.4	60	95	171.7	53	93
Fe	199.0	50	91	261.2	54	92

Source: Baligar, V.C. et al., *Agron. J*., 79, 1038, 1988.

[a] Altaswede is a mammoth or single-cut Canadian cultivar; Kenstar is a medium- or double-cut U.S. cultivar.

[b] U = mg per 10 plants for P, S, K, Ca, Mg, and µg per 10 plants for Mn, Fe.

uptake. Inter- and intraspecific differences in plant growth and mineral composition due to Al levels in the rooting medium have been well documented in the literature (Foy, 1984). Data in Table 18.19 show the percent inhibition of essential elements in several species of legumes and grasses due to the presence of 100 µM Al in the growth medium. In all these forage species, Al inhibited the uptake of essential nutrients. Data in Table 18.20 highlight the effects of different levels of Al in the growth medium on the uptake of various elements in two morphologically different red clover cultivars. In both red clover cultivars, increasing the Al levels in the growth medium inhibited uptake of essential nutrients. Such reductions in uptake are also related to decreased dry matter accumulation of the shoot.

18.7 SUMMARY

Forages play an important role in world food resources by supplying feed to livestock and consequently meat and milk for human consumption. A grassland ecosystem is an excellent example of a renewable resource, and, if properly managed, the system may be productive over a very long time. A first principle of modern pasture management is the association of forage grasses with legumes can improve forage quality. In forage systems that do not use N fertilizer, addition of a legume component can increase soil fertility and pasture production. The use of legumes in pasture may also result in increased N content, greater digestibility, and a higher well balanced mineral content of herbage, all of which are important in animal nutrition. Grass–legume associations are used in many parts of the world because the legume improves forage quality and production, which results in greater animal production. Grass–legume forage mixtures may have other advantages compared to pure grasses or pure legumes, including erosion and weed control and increased stand longevity. Due to the competition of grasses with legumes in mixed swards, careful management is often needed to maintain the mixture. It is necessary to select grasses and legumes appropriate to the climatic and soil environment, fertilizer treatments, and grazing management.

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19 Cover Crops

19.1 INTRODUCTION

Increasing crop productivity and maintaining a clean environment are major challenges to agricultural scientists in the twenty-first century. To meet these challenges, crop production practices need to favor higher yields and minimized environmental pollution (Fageria et al., 2005; Fageria, 2009). The use of cover crops in cropping systems is an important strategy to help achieve these objectives. Cover crops can be defined as close-growing crops that provide soil protection and help improve soil characteristics between periods of normal crop production, or between trees in orchards and vines in vineyards (Soil Science Society of America, 1997). When plowed under and incorporated into the soil, cover crops may be referred to as green manure crops. Cover crops may be grown in rotation with normal cash crops, or they may be grown simultaneously in association with cash crop. In plantation farming, quick-growing perennial cover crops are planted before or during early stages of plantation crop establishment.

The beneficial effects of cover crops on soil quality and the yields of succeeding crops have long been known (Odland and Knoblauch, 1938). After World War II, chemical fertilizers began to replace cover crops because fertilizers were economical and required less management than cover crops. During 1960s, a term "green revolution" was used when grain yield of important crops like rice, wheat, and corn increased dramatically in developed as well as developing countries as a result of improved varieties and increased use of chemical fertilizers and irrigation. For several decades, these "green revolution" crops were planted in monoculture with little consideration of appropriate crop rotations, green manuring, or and cover crops.

In recent years, the high cost of chemical fertilizers, interest in organic agriculture, soil degradation, and contamination of streams by fertilizers and pesticides have stimulated renewed interest in cover crops and green manures (Fageria et al., 2005; Baligar and Fageria, 2007; Fageria, 2007). Cover crops reduce environmental risks such as soil erosion (Johnson et al., 1998; Kaspar et al., 2001) and nitrate leaching (Owens et al., 2000; De Bruin et al., 2005; Feyereisen et al., 2006; Collins et al., 2007). In addition, cover crops can conserve soil moisture, reduce diurnal fluctuations in soil temperature (Teasdale and Mohler, 1993; Baligar and Fageria, 2007), and control weeds (Ateh and Doll, 1996; Williams et al., 1998; Fageria et al., 2005; Baligar and Fageria, 2007; Fageria, 2007). Cover crops have been shown to break disease and pest cycles, reducing the need for fungicide and insecticide application (Snapp et al., 2005).

Cover crops are generally included in cropping systems as nutrient management tools and can be leguminous or nonleguminous (Ruffo and Bollero, 2003; Sogbedji et al., 2006). Uptake of mineral N by cover crops can reduce NO_3 leaching and erosion. In addition, biological N fixation by leguminous cover crops usually reduces the need for N fertilizer by the succeeding crop. Mixtures of a legume and a grass can be used to provide both benefits simultaneously (Fageria et al., 2005). Major cover crops of tropical and temperate regions are listed in Table 19.1.

This chapter reviews recent advances in the use and management of cover crops and discusses their potential benefits and drawbacks for annual crop production and sustained soil quality. It also reviews their climate and soil requirements, morphology, growth, development, and nutrient requirements.

TABLE 19.1
Major Cover Crops of Tropical and Temperate Regions

Tropical Region		Temperate Region	
Common Name	**Scientific Name**	**Common Name**	**Scientific Name**
Sunn hemp	*Crotalaria juncea* L.	Hairy vetch	*Vicia villosa* Roth
Sesbania	*Sesbania aculeata* Retz Poir	Barrel medic	*Medicago truncatula* Gaertn
Sesbania	*Sesbania rostrata* Bremek & Oberm	Alfafa	*Medicago sativa* L.
Cowpea	*Vigna unguiculata* L. Walp.	Black lentil	*Lens culinaris* Medikus
Soybean	*Glycine max* L. Merr.	Red clover	*Trifolium pratense* L.
Cluster bean	*Cyamopsis tetragonoloba*	Soybean	*Glycine max* L. Merr.
Alfalfa	*Medicago sativa* L.	Faba bean	*Vicia faba* L.
Egyptian clover	*Trifolium alexandrium* L.	Crimson clover	*Trifolium incarnatum* L.
Wild indigo	*Indigofera tinctoria* L.	Ladino clover	*Trifolium repens* L.
Pigeon pea	*Cajanus cajan* L. Millspaugh	Subterranean clover	*Trifolium subterraneum* L.
Mung bean	*Vigna radiata* L. Wilczek	Common vetch	*Vicia sativa* L.
Lablab	*Lablab purpureus* L.	Purple vetch	*Vicia benghalensis* L.
Gray bean	*Mucuna cinerecum* L.	Cura clover	*Trifolium ambiguum* Bieb.
Buffalo bean	*Mucuna aterrima* L. Piper & Tracy	Sweet clover	*Melilotus officinalis* L.
Crotalaria breviflora	*Crotalaria breviflora*	Winter pea	*Pisum sativum* L.
White lupin	*Lupinus albus* L.	Narrowleaf vetch	*Vicia angustifolia* L.
Milk vetch	*Astragalus sinicus* L.	Milk vetch	*Artragalus sinicus* L.
Crotalaria	*Crotalaria striata*		
Zornia	*Zornia latifolia*		
Jack bean	*Canavalia ensiformis* L. DC.		
Tropical kudzu	*Pueraria phaseoloides* (Roxb.) Benth.		
Velvet bean	*Mucuna deeringiana* Bort. Merr.		
Adzuki bean	*Vigna angularis*		
Brazilian stylo	*Stylosanthes guianensis*		
Jumbiebean	*Leucaena leucocephala* Lam. De Wit		
Desmodium	*Desmodiumovalifolium* Guillemin & Perrottet		
Pueraria	*Pueraria phaseoloides* Roxb.		

Source: Fageria, N.K. et al., *Commun. Soil Sci. Plant Anal*., 36, 2733, 2005.

19.2 CLIMATE AND SOIL REQUIREMENTS

Solar radiation, temperature, rainfall are the major climatic factors that influence growth, development, and persistence of cover crops. Rainfall and temperature requirements of tropical and temperate cover crops are listed in Tables 19.2 and 19.3. The growth pattern of cover crops is largely influenced by temperature. Most tropical cover crops are adapted to temperatures ranging from 10°C to 35°C, and temperate cover crops grow well at temperatures from 4°C to 28°C. Cover crops have varying degree of tolerance to drought and waterlogging.

Both tropical (Table 19.4) and temperate (Table 19.5) cover crops differ in their responses to soil pH. Table 19.6 gives the responses of 14 tropical legume cover crops grown on a Brazilian Oxisol to soil pH. Similarly, Figure 19.1 shows growth of pigeon pea on soils with different pH values. The decrease in shoot dry weights of several species with decreasing acidity indicates that these legumes were tolerant to soil acidity, possibly because they were selected under acid soil conditions. Similarly, variation if Al tolerance among wheat cultivars is correlated with their origin (Foy, 1984; Garvin and Carver, 2003).

TABLE 19.2
Growth Habit, Rainfall, and Temperature Requirement of Cover Crops Adapted to Tropical Plantations and Row Crops

Common Name	Rainfall (mm)	Temperature (°C)
Plantation Crops		
Velvet bean (A/P, H/S)	400–2000	15–35
Butterfly pea (P, H)	500–2000	15–35
Calopo (P, H)	900–4000	18–36
Centro (P, H)	1000–2000	22–26
Cowpea (A/P, H)	300–4100	12–35
Showy crotalaria (A/P, S)	900–2800	12–28
Smooth crotalaria (A/P, S)	900–2800	12–28
Sunn hemp (A, S)	500–4300	8–35
Ea-Ea (P, H)	900–4500	20–30
Flemingia (P, S)	1100–3500	12–36
Hairy indigo (A/P, S)	900–2500	15–28
Jack bean (P, H)	640–4250	15–30
Joint-vetch (A/P, S)	800–2500	10–27
Perennial peanut (P, H)	1000–2000	22–28
Sesbania (P, S)	500–2000	7–30
Brazilian lucerne (P, S)	700–5000	15–27
Stylo, capitata (P, S)	500–2500	15–30
Stylo, macrocephala (P, S)	1000–1900	21–25
Vogel's tephrosia, (P, S)	850–2500	12–29
White tephrosia (P, S)	700–2500	18–28
Tropical kudzu (P, H)	900–2500	12–30
Row Crops		
Cowpea	390–above	20–30
Pigeon pea	Dry to 500/crop	20–30
Mung bean	Dry to 410/crop	20–34
Moth bean	50–60	25–30
Guar	590/crop	24–30
Annual peanut	>500	24–33
Lablab bean	200–2500	22–35
Tepary bean	500–600	20–30
Lima bean	Drought tolerant	20–30
Black gram	<900	8–22
Egyptio clover	380–1660	7–30
Adzuki bean	530–1730	20–30
Rice bean	1000–1500	18–30
Sesbania	570–2210	20–30
Perlmillet	200–800	10–35
Sorghum	400–1000	21–30

(*continued*)

TABLE 19.2 (continued)
Growth Habit, Rainfall, and Temperature Requirement of Cover Crops Adapted to Tropical Plantations and Row Crops

Sources: Duke, J.A., *Handbook of Legumes of World Economic Importance,* Plenum Press, New York, 1981; Skerman, P.J. et al., (eds.), *Tropical Forage Legumes,* FAO-United Nations, Rome, Italy, 1988; Van der Maesen, L.J.G. and Somaatmadja, S., (eds.), *Plant Resources of South-East Asia, No. 1*, *Pulses,* Pudoc, Wageningen, the Netherlands, 1989; Faridah Hanum, I. and van der Maesen, L.J.G., (eds.), *Plant Resources of South-East Asia, No. 11, Auxiliary Plants,* Backhuys Publishers, Leiden, the Netherlands, 1997; Wiersema, J.H. and Leon, B., *World Economic Plants: A Standard Reference*, CRC Press, Boca Raton, FL, 1999; LEXSYS, *Decision Support for the Selection of Legumes for Incorporation into Tropical Cropping Systems*, International Institute of Tropical Agriculture, Ibadan, Nigeria and the School of Environment and Natural Resources, University of Wales, Bangor, U.K., 2003; Cook, B.G. et al., Tropical forages: An interactive selection tool, 2005, available at http://www.tropicalforages.info/key/Forages/Media/Html/index.htm, accessed October 20, 2006; Lewis, G.B. et al., *Legumes of the World*, Kew Publishing, Richmond, Surrey, U.K., 2005; Roskov, Y.R. et al., (eds.), ILDIS legume web, 2005, available at http://www.ildis.org/, accessed November 6, 2006; USDA-ARS, Germplasm resources information network (GRIN), 2006, available at http://www.ars-grin.gov/cgi-bin/npgs/html/tax_search.pl, accessed November 8, 2006; FAO, Grassland species database, 2007, available at http://www.fao.org/AG/AGp/agpc/doc/Gbase/Default.htm, accessed January 5, 2007; Fageria, N.K. et al., *Commun. Soil Sci. Plant Anal*., 36, 2733, 2005.

A, annual; P, perennial; H, herb; S, shrub.

TABLE 19.3
Rainfall and Temperature Requirement of Temperate Region Legume Cover Crops

Species	Rainfall (mm)	Temperature (°C)
Hairy vetch	310–1660	4–21
Alfala	500–2700	4–27
Red clover	300–1900	5–20
Cura clover	500–1200	8–13
Ladino clover	300–1900	4–22
Subterranean clover	430–1000	0–25
Faba bean	300–2090	6–28
Berseem clover	400–1700	7–27
Cowpeas	400–2000	13–28
Crimson clover	300–1600	6–21
Field peas	100–2800	5–28
Sweet clover	300–1600	5–22
White clover	100–1600	8–24

Sources: Duke, J.A., *Handbook of Legumes of World Economic Importance*, Plenum Press, New York, 1981; LEXSYS, *Decision Support for the Selection of Legumes for Incorporation into Tropical Cropping Systems*, International Institute of Tropical Agriculture, Ibadan, Nigeria and the School of Environment and Natural Resources, University of Wales, Bangor, U.K., 2003; Baligar, V.C. and Fageria, N.K., *J. Plant Nutr*., 30, 1287, 2007.

TABLE 19.4
Adequate Soil and pH for Tropical Cover Crops

Cover Crops	Soil and pH	Cover Crops	Soil and pH
Velvet bean	Well drained, medium fertility pH 5.0–8.0	Cowpea	Well drained sandy loam, alkaline and acidic soils, pH 5.0–8.0
Butterfly pea	Loamy sand to silty, wee drained, adapted to acid infertile soils. pH 5.0–8.0	Pigeon pea	Sandy to heavy clay soils, well drained heavy to light textured soils, pH 5.0–8.0
Calopo	Clay to wide range soil types, adapt to acid soils. No saline soils pH 5.0–8.0	Mung bean	Wide rage well drained non acidic soil, pH 5.8–6.5
Centro	Well drained low to medium fertility soils, tolerant to soil acidity	Moth bean	Well drained sandy to sandy loam, alkaline soils, pH 5.0–8.0
Cowpea	Sandy to well drained clay soils pH 4.0–8.0	Guar	Fertile medium textured, sandy loam well drained, pH 5.5–8.0
		Annual peanut	Clay to fine sand, alkaline, acidic, pH 5.0–5.5
Showy crotalaria	Wide range of soils pH 4.8–8.0	Lablab bean	Acidic to alkaline, pH 4.4–7.8
Smooth crotalaria	Wide range of soils with adequate levels of Mg, pH 4.5–8.0	Tepary bean	Wide range of soils tolerant susceptible to salinity, pH 5.0–7.1
Sunn hemp	Well drained soils, pH 4.5–8.4	Lima bean	Well drained sandy loam
Ea-Ea	Low fertility acid soils, pH 4.0–7.0	Black gram	Loamy to clay, pH around 6.2
Flemingia	Low fertility acid soils, pH 4.0–8.0	Egyption clover	Sandy loam to clay No salinity, pH
Hairy indigo	Well drained soils, pH 5.8–8.0	Adzuki bean	Sandy loam, well drained soils, pH 5.0–7.5
Jack bean	Wide range, salinity tolerant, pH 4.5–8.0	Rice bean	Loamy soils, pH 6.8–7.5
Joint-vetch	Sandy to clay soils, pH 4.0–8.0	Sesbania	Wide range soils, saline soils, pH 5.6–9.3
Perennial peanut	Wide range of low fertility soils, low tolerant to salinity, pH 4.5–7.2	Perlmillet	Well drained clay to sandy soils, pH 5.0–7.0
Sesbania	Sandy to clay, tolerant to salinity, pH	Sorghum	Sandy loam to heavy clay, pH 5.0–8.5
Brazilian lucerne	Sandy to clay, tolerant to acidity, pH 4.0–8.3		
Stylo, capitata	Sandy to clay loam, tolerate acidity, pH 4.0–5.5		
Stylo, macrocephala	Sandy soil with low P and pH 4.0–6.0		
Vogel's tephrosia	Well drained sandy to low fertility soils, pH 4.5–6.5		
White tephrosia	Sandy low fertility soils, pH 3.5–8.0		
Tropical kudzu	Heavy acidic soils, intolerant to salinity, pH 4.3–8.0		

(*continued*)

TABLE 19.4 (continued)
Adequate Soil and pH for Tropical Cover Crops

Sources: Duke, J.A., *Handbook of Legumes of World Economic Importance*, Plenum Press, New York, 1981; Skerman, P.J. et al., (eds.), *Tropical Forage Legumes*, FAO-United Nations, Rome, Italy, 1988; Van der Maesen, L.J.G. and Somaatmadja, S., (eds.), *Plant Resources of South-East Asia, No. 1, Pulses*, Pudoc, Wageningen, the Netherlands, 1989; Faridah Hanum, I. and van der Maesen, L.J.G., (eds.), *Plant Resources of South-East Asia, No. 11, Auxiliary Plants*, Backhuys Publishers, Leiden, the Netherlands, 1997; Wiersema, J.H. and Leon, B., *World Economic Plants: A Standard Reference*, CRC Press, Boca Raton, FL, 1999; LEXSYS, *Decision Support for the Selection of Legumes for Incorporation into Tropical Cropping Systems*, International Institute of Tropical Agriculture, Ibadan, Nigeria and the School of Environment and Natural Resources, University of Wales, Bangor, U.K., 2003; Cook, B.G. et al., Tropical forages: An interactive selection tool, 2005, available at http://www.tropicalforages.info/key/Forages/Media/Html/index.htm, accessed October 20, 2006; Lewis, G.B. et al., (eds.), *Legumes of the World*, Kew Publishing, Richmond, Surrey, U.K., 2005; Roskov, Y.R. et al., (eds.), ILDIS legume web, 2005, available at http://www.ildis.org/, accessed November 6, 2006; USDA-ARS, Germplasm resources information network (GRIN), 2006, available at http://www.ars-grin.gov/cgi-bin/npgs/html/tax_search.pl, accessed November 8, 2006; FAO, Grassland species database, 2007, available at http://www.fao.org/AG/AGp/agpc/doc/Gbase/Default.htm, accessed January 5, 2007; Fageria, N.K. et al., *Commun. Soil Sci. Plant Anal*., 36, 2733, 2005.

Cover crops are adapted to a wide range of soil types, but most require well-drained soils for optimum growth. Phosphorus deficiency is one of the most widespread constraints to cover crop establishment, persistence, and production. Among temperate crops, cura clover, ladino clover, faba bean, oats, rye, and buckwheat are very acid soil tolerant and could grow at soil pH as low as 4.5. Hairy vetch, subterranean clover, cowpeas, and crimson clovers grow best at soil pH values of 5.5 and above (Clark, 2007).

19.3 RESPONSE TO ABIOTIC AND BIOTIC FACTORS

In many lowland tropical regions, extreme climatic factors (warm temperatures, high rainfall during the wet season, and little precipitation during the dry season), poor management practices (removal or incorporation of crop residues, inadequate fertilizer and lime inputs), excessive erosion and leaching losses of nutrients, and loss of organic matter have contributed to declining soil fertility and increasing soil acidity. Abiotic factors such as soil acidity, mineral deficiencies (P, Ca, Mg, Fe, Zn) and toxicities (Al, Mn), drought, and high temperatures strongly affect cover crop growth, development, and nutrient uptake (Baligar et al., 2001). Inter- and intraspecific differences in crop growth and nutrient use efficiency in response to abiotic factors are well documented (Foy, 1984; Alam, 1999; Pessarakli, 1999). Some of the tropical cover crops are known to tolerate soil acidity (calopo, centrocema, cowpea, ea ea, flemingia, joint vetch, perennial peanut, sesbania, Brazilian lucerne), drought (butterfly pea, calopo, centro, cowpea, crotalaria, sunhemp, flamingia, jack bean, joint vetch, Brazilian lucerne), and water logging (calapo, ea-ea, flemingia, jack bean, joint vetch) (Duke, 1981; Skerman et al., 1988; Van der Maesen and Somaatmadja, 1989; Faridah Hanum and van der Maesen, 1997; Wiersema and Leon, 1999; LEXSYS, 2003; Cook et al., 2005; Lewis et al., 2005; Roskov et al., 2005; USDA-ARS, 2006; FAO, 2007). Some temperate cover crops also tolerate soil acidity (oats, rye, buckwheat, crimson clover, white clover and cowpea), drought (barley, rye, sorghum, mustard, cowpea, medics, subterranean clover, wollypod vetch), flooding (annual ryegrass, oats, rye, sorghum-sudan grass, berseem clover, red clover, subterranean clover, white clover, woollypod vetch), and high temperatures (barley, sorghum, berseem clover, cowpea, medics, sweet clover, wollypod vetch) (Clark, 2007).

TABLE 19.5
Adequate Soil and pH for Temperate Cover Crops

Species	Soil and pH
	Legume
Hairy vetch	Adapted to loamy sands or sandy loams of moderate-low fertility, pH 5.5–7.5
Alfala	Well drained, non-alkaline, non-acidic, fertile soils, pH 6.0–7.0
Red clover	Grows in well-drained loamy soils pH 6.2–7.0
Cura clover	Noncalcareous clays and clay loams, pH 4.5–7.3
Ladino clover	Clay and loam soils pH 4.5–8.2
Subterranean clover	Thrives in low to moderate fertile soils, moderate acidic to slightly alkaline soils, pH 5.5–7.0
Faba bean	Adapted to sandy loams and loamy clays of moderate fertility, pH 4.5–8.3
Berseem clover	Slightly alkaline loam and silty soils, pH 6.2–7.0
Cowpeas	Well-drained, highly acidic to neutral soils, adapted to high alkaline soils, pH 5.5–6.5
Crimson clover	Well-drained sandy loam, heavy clay, able to tolerate high acidity and alkalinity and water logging, pH 5.5–7.0
Field peas	Well-drained, heavy loam soils near neutral pH, pH 6.0–7.0
Sweet clover	Loam soils with neutral pH, thrives in poorly drained soils pH 6.5–7.5
White clover	Tolerates wet soils including short flooding, survives on medium to acid soils, grows better in clay and loam soils than sandy soils, pH 6.0–7.0
Woollypod vetch	Tolerates moderately acidic and alkaline soils, grows on poor sandy soils, pH 6.0–8.0
	Nonlegume
Annual ryegrass	Well-drained, fertile sandy loam soil, pH 6.0–7.0
Barley	Well-drained, fertile loamy or light clay soil pH 6.0–8.5
Oats	Moderately fertile soils, pH 4.5–7.5
Rye	Light loams, sandy soils, pH 5.0–7.0
Wheat	Well-drained, medium texture and moderately fertile soils pH 6.0–7.5
Buck wheat	Light to medium well-drained sandy loams, loams, or silt loams, pH 5.0–7.0
Sorghum-sudan grass	Fertile, and near-neutral soils, pH 6.0–7.0

Sources: Clark, A. (ed.), *Managing Cover Crops Profitably* (Sustainable Agricultural Network Handbook Series Book 9), 3rd edn., Scientific Agricultural Network, Beltsville, MD, 2007; LEXSYS, *Decision Support for the Selection of Legumes for Incorporation into Tropical Cropping Systems*, International Institute of Tropical Agriculture, Ibadan, Nigeria and the School of Environment and Natural Resources, University of Wales, Bangor, U.K., 2003; Duke, J.A., *Handbook of Legumes of World Economic Importance*, Plenum Press, New York, 1981.

Persistence of understory cover crops in plantation crops depends on the amount and quality of light reaching their canopies, and those that tolerate low irradiance have better chance of growing and persisting under plantation crops. Both inter- and intraspecific differences in shade tolerance have been reported for tropical (Wang et al., 1985; Shelton et al., 1987; Stur, 2001) and temperate cover crops (Ingels et al., 1998; Clark, 2007). Tropical cover crops with good shade tolerance include velvet bean, calop, centro, crotalaria, ea-ea, flemingia, hairy indigo, jack bean, joint vetch, perennial peanut, susbania, white tephrosia and tropical kudzu (Skerman et al., 1988; LEXSYS, 2003; Cook et al., 2005; Lewis et al., 2005; FAO, 2007). Shade-tolerant temperate cover crops include annual ryegrass, rye, berseem clover, crimson clover, medic, subterranean clover, and white clover (Clark, 2007).

Cover crops may provide good habitat for beneficial insects (Bugg et al., 1991) and reduce parasitic nematode populations. Many diseases and pests attack cover crops; therefore, selection of right cover crop is essential to reduce losses from diseases and pests (Duke, 1981; Skerman et al., 1988; LEXSYS, 2003; Cook et al., 2005; Lewis et al., 2005; Roskov et al., 2005; USDA-ARS, 2006; Clark, 2007; FAO, 2007).

TABLE 19.6
Shoot Dry Weight (g Plant^{-1}) of 14 Tropical Legume Cover Crops at Three Acidity Levels

Legume Species	High Acidity (pH 5.5)	Medium Acidity (pH 6.5)	Low Acidity (pH 7.0)	Average
Short-flowered crotalaria	4.04d	1.97fg	0.91	2.31gh
Sunn hemp	12.32bc	7.76cde	4.23bc	8.10cdef
Smooth crotalaria	4.24d	2.87efg	1.41cd	2.84gh
Showy crotalaria	5.80d	4.35defg	3.74bcd	4.63fgh
Crotalaria	13.05bc	6.12cdef	3.44bcd	7.53def
Calapo	4.88d	3.11defg	1.82cd	3.27gh
Pigeon pea	7.80cd	5.45cdefg	4.09bc	5.78efg
Lablab	14.31b	10.39bc	5.80b	10.17bcd
Mucuna bean ana	12.99bc	8.39bcd	4.32bc	8.57cde
Black mucuna bean	16.39ab	13.46b	6.48b	12.11b
Gray mucuna bean	15.13b	13.79b	4.47bc	11.13bc
Jack bean	21.43a	19.78a	13.52a	18.24a
Tropical kudzu	3.76d	1.61fg	0.92cd	2.09h
Brazilian lucerne	3.95d	0.32g	0.18d	1.48h
Average	10.00	7.09	3.95	6.69
F-test				
Soil acidity (S)		**		
Legume species (L)		**		
S × L		**		

Source: Fageria, N.K. et al., *Commun. Soil Sci. Plant Anal*., 40, 1148, 2009.

Note: Means followed by the same letter in the same column are not significantly different by Tukey's test at the 5% probability level.

** Significant at the 1% probability level.

19.4 BENEFICIAL EFFECTS OF COVER CROPS

Planting cover crops before or between commercial crops as well as between trees or shrubs of plantation crops can improve the soil's physical, chemical, and biological properties and consequently lead to improved soil health and yield of the principal crops. Leaving cover crops as surface mulches in no-till crop production systems has the advantage of reducing N leaching (Smith et al., 1987), conserving soil moisture (Morse, 1993), reducing soil erosion (Langdale et al., 1991), improving soil physical properties (Blevins and Frye, 1993), increasing nutrient retention (Dinnes et al., 2002), increasing soil fertility (Cavigelli and Thien, 2003), suppressing weeds (Creamer and Baldwin, 2000), reducing diseases and insects (Ristaino et al., 1996), reducing global warming potential (Robertson et al., 2000), and increasing crop yields (Triplett et al., 1996). These beneficial effects of cover crops on soil management and crop productivity are discussed in the following sections.

19.4.1 Soil Erosion Control

Soil loss by wind and water erosion caused by poor soil management is by far the largest single factors contributing to deterioration of soil's physical, chemical, and biological properties and to further decline in productivity of most crop lands. Sloping land, without protection of vegetative cover, leads to soil loss by sheet, rill, and gully erosion. Soil erosion removes surface soil layers, which contain most of the soil organic matter (SOM) and immobile nutrients. Loss of top soil reduces soil fertility, ultimately reducing crop productivity. Cover crops provide vegetative cover,

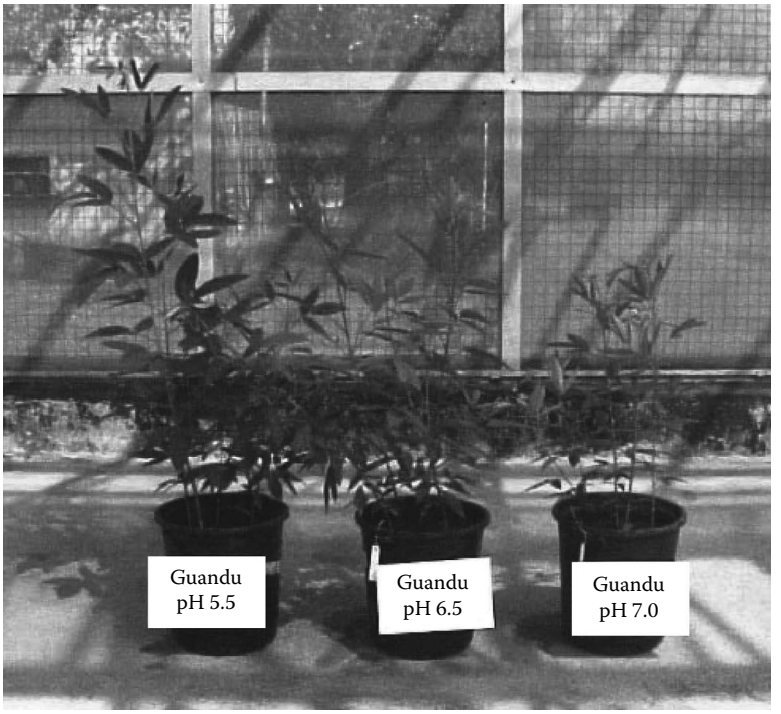

FIGURE 19.1 Growth of pigeon pea under different pH grown on a Brazilian Oxisol.

thereby shielding the soil surface from rain drop impact. If the soil surface is not protected by leaves or crop residues, rain drops compact the soil surface, forming a soil crist that reduces water infiltration, and increases runoff and soil erosion. During the establishment phase of plantation cropping systems, the soil is largely exposed due to wide spacing of small plants between and within rows. Under such circumstances, there can be considerable loss of surface soil, nutrients, and organic matter through soil erosion. Cover crops that grow rapidly and provide good soil cover can reduce soil erosion and increase SOM content. Ground cover provided by cover crops protects the surface soil from raindrop impact and prevents sealing and crusting of the soil surface. Increasing SOM increases water infiltration and soil water-holding capacity, thereby reducing soil erosion. In temperate regions, the role of cover crops in reducing soil erosion is well documented (Langdale et al., 1991; Shanks et al., 1998). In tropical region, tropical kudzu and mucuna reduced soil erosion (Carsky et al., 2001; Tian et al., 2001).

19.4.2 Soil Physical Properties and Water-Holding Capacity

Soil structure is an important component of soil health. Cover crops add substantial amounts of organic matter to soil through decomposition of their residues and roots (Kirchner et al., 1993; Wagger et al., 1998). Organic matter stabilizes formation and stabilization of soil aggregates. Stable aggregates increase water infiltration, water-holding capacity, and aeration, as well as reduce bulk density, thereby reducing resistance to root penetration (Fageria et al., 2005). Improved soil structure promotes better root growth and plant nutrient absorption, increases soil moisture, and improves soil microbial activities for better nutrient mineralization (N`Dayegamiye, 2006). Tropical kudzu grown as an alley crop between the rows of field crops improves soil aggregate stability and decreases soil bulk density (Tian et al., 2001). Crop residues on the soil surface increase soil moisture by increasing infiltration and decreasing loss of moisture by evaporation. In tropical Africa, flemingena used as an alley crop significantly increases soil moisture retention and lowers

soil temperature (Banful et al., 2000). Reduction of soil temperature reduces the high rates of SOM decomposition, thereby improving soil biological activity and enhancing nutrient supply.

19.4.3 Soil Organic Matter

Organic matter directly affects the soil's ability to support continued crop production (Bauer and Black, 1994; Lal, 1998). Cover crops supply organic matter to the soil through decomposition of their residues and roots. Dry matter produced by tropical cover crops varies from 3 to 20 Mg ha^{-1} $year^{-1.}$ (Baligar and Fageria, 2007). Cover crops are known to increase soil organic C on an average of 2 g kg^{-1} more than fallow (Fageria et al., 2005). The rate of crop residue decomposition and persistence of SOM in soil are greatly influenced by the prevailing temperature, moisture conditions, and activities of soil fauna. SOM plays a direct role in formation and stability of soil aggregates, greatly affecting water infiltration, retention, and aeration. SOM also influences soil pH, nutrient cycling, cation exchange capacity, and binding phytotoxic ions such as aluminum and manganese. Soil organic carbon is an important terrestrial pool for carbon storage and exchange with atmospheric CO_2 (Follett, 2001). Cover crops help reduce global warming by sequestration of atmospheric CO_2 in soils (Lal and Kimble, 1997).

19.4.4 Nitrogen Economy and Soil Fertility

Legume cover crops can fix substantial amounts of atmospheric N, reducing N fertilizer needs for succeeding cash crops (Singh et al., 1992). Two bacterial species, *Rhizobium* and *Bradyrhizobium*, are responsible for symbiotic N fixation in legumes. The amount of N fixed by cover crops is determined largely by the genetic potential of the legume species, the amount of mineral N in the soil, and other factors affecting crop growth, such as temperature, soil moisture, and solar radiation. In tropical regions drought, high temperatures, and soil acidity complexes (low pH, high exchangeable Al and Mn, low soil fertility) are the main factors limiting N_2 fixation (Izaguirre-Mayoral et al., 1995). Cover crops accumulate N by uptake of available inorganic soil N and, if they are legumes, by fixing atmospheric N. Table 19.7 gives typical quantities of N fixed by

TABLE 19.7
Quantity of Nitrogen Fixed by Legume Cover Crops

Crop Species	N_2 Fixed (kg ha^{-1} $Crop^{-1}$)	Reference
Peanut (*Arachis hypogaea* L.)	40–80	Brady and Weil (2002)
Cowpea (*Vigna unguiculata* L. Walp.)	30–50	Brady and Weil (2002)
Alfalfa (*Medicago sativa* L.)	78–222	Heichel (1987)
Soybean (*Glycine max* L.)	50–150	Brady and Weil (2002)
Fava bean (*Vicia faba* L.)	177–250	Heichel (1987)
Hairy vetch (*Vicia villosa* Roth.)	50–100	Brady and Weil (2002)
Ladino clover (*Trifolium repens* L)	164–187	Heichel (1987)
Red clover (*Trifolium pratense* L.)	68–113	Heichel (1987)
White lupin (*Lupinus albus* L.)	50–100	Brady and Weil (2002)
Field peas (*Pisum sativum* L.)	174–195	Heichel (1987)
Chickpea (*Cicer arietinum* L.)	24–84	Heichel (1987)
Pigeon pea (*Cajanus cajan* L. Huth.)	150–280	Brady and Weil (2002)
Kudzu (*Pueraria phaseoloides* Roxb. Benth)	100–140	Brady and Weil (2002)
Green gram (*Vigna radiata* L. Wilczek.)	71–112	Chapman and Myers (1987)
Lentil (*Lens culinaris L.*)	57–111	Smith et al. (1987)

TABLE 19.8
Dry Matter Yield and N Uptake by Cover Crops

Crop Species	Dry Matter Yield (Mg ha^{-1})	N Uptake (kg ha^{-1})
Hairy vetch	5.1	209
Bigflower vetch	1.9	60
Crimson clover	2.4	56
Berseem clover	1.5	45
Australian winter pea	1.6	68
Common vetch	4.3	134
Subterranean clover	4.0	114
Rye	6.3	100
Wheat	1.5	29

Source: Compiled from Frye, W.W. et al., Role of annual legume cover crops in efficient use of water and nitrogen, in *Cropping Strategies for Efficient Use of Water and Nitrogen*, Hargrove, W.L. (ed.), Special Publication No. 51, ASA, Madison, WI, 1988.

different leguminous cover crops. The N provided by legume cover crops is sometimes adequate to produce optimum yields of subsequent nonleguminous crops; however, high-yielding cereals such as corn (*Zea mays* L.) generally need supplemental N fertilizer.

Table 19.8 gives typical values of dry matter production and N uptake by different cover crops. Table 19.9 provides data of nitrogen fertilizer equivalence (NFE) of legume cover crops to succeeding nonlegume crops. The NFE values varied from 12 to 182 kg ha^{-1}. Smith et al. (1987) reported that NFE values range from 40 to 200 kg ha^{-1}, but more typically are between 75 and 100 kg ha^{-1}. For example, interseeding red clover (*Trifolium pretense* L.) into small grains is a common practice in the northeastern United States (Singer and Cox, 1998), and this practice can provide up to 85 kg N ha^{-1} to the subsequent corn crop (Vyn et al., 1999). Researchers in the southeastern United States have estimated that legumes such as hairy vetch can supply well over 100 kg N ha^{-1} to following corn or grain sorghum crop (Blevins et al., 1990; Oyer and Touchton, 1990). On prairie soils in Kansas, Sweeney and Moyer (1994) found that grain sorghum following initial kill-down of red clover and hairy vetch yielded as much as 131% more than continuous sorghum, with estimated fertilizer N equivalencies exceeding 135 kg ha^{-1}.

Most legume cover crops need inoculation with an appropriate strain of N fixing bacteria to make them efficient in fixing N_2. For example, *Rhizobium meliloti* is effective for alfalfa and sweet clover and, *Rhizobium japonicum* is used for cowpea and peanut. For clover *Rhizobium trifoli* and for pea *Rhizobium leguminosarm* are effective. Legume and nonlegume cover crops reduce potential for NO_3 leaching. Rye (*Secale cereale* L.), with its rapid establishment of an extensive root system, was more effective in reducing NO_3 leaching losses than vetch (*Vicia villosa* Roth) (Fageria et al., 2005).

Cover crops are also known to improve P availability to succeeding crops grown on acid soils by converting nonavailable mineral P to more available organic P. Mineralization of organic P in crop residue could provide a relatively labile P source that is easily available to companion plantation or row crops. Organic compounds released during decomposition process may increase P availability by blocking P adsorption sites and/or complexing with exchangeable Al in acid soils. Cover crop impacts on the soil's chemical (reduced pH, increased SOM), physical (low temperature, high moisture content), and biological properties can have beneficial effects on mineral cycling and increase levels of organically bound and inorganic nutrients. Legumes also explore subsoil nutrient pools, capture available nutrients with their extensive root systems, and transfer those nutrients to the soil surface in their residues (Gathumbi et al., 2003).

TABLE 19.9
Nitrogen Fertilizer Equivalence (NFE) of Legume Cover Crops to Succeeding Nonlegume Crops

Legume/Nonlegume Crop	NFE (kg ha^{-1})
Hairy vetch/cotton	67–101
Hairy vetch + rye/corn	56–112
Hairy vetch/corn	78
Hairy vetch/sorghum	89
Hairy vetch/corn	78
Hairy vetch + wheat/corn	56
Crimson clover/cotton	34–67
Crimson clover/corn	50
Crimson clover/sorghum	19–128
Common vetch/sorghum	30–83
Bigflower vetch/corn	50
Subterranean clover/sorghum	12–103
Sesbania/lowland rice	50
Alfalfa/corn	62
Alfalfa/wheat	20–70
Arachis spp./wheat	28
Subterranean clover/wheat	66
White lupin/wheat	22–182
Arachis spp./corn	60
Pigeon pea/corn	38–49
Sesbania/potato	48
Mung bean/potato	34–148
Chickpea/wheat	15–65

Sources: Compiled from Smith, M.S. et al., *Adv. Soil Sci*., 7, 95, 1987; Kumar, K. and Goh, K.M., *Adv. Agron*., 68, 197, 2000.

Delegado (1998) showed that winter cover rye (*Secale cerale* L.) could scavenge residual soil NO_3^- from the soil profile to minimize NO_3^- leaching losses. Similar results have been observed in other crop production systems (Holderbaum et al., 1990; Meisinger et al., 1991). Collins et al. (2007) reported that a mustard cover crop can provide 30–40 kg N ha^{-1} toward the N requirement of a subsequent potato crop. Cover crops can recover 150–300 kg N ha^{-1} from the soil profile and return this N to the soil surface (Ditch et al., 1993; Bundy and Andraski, 2005).

19.4.5 Soil Biological Activity

Meso, macro, and micro fauna in soil play crucial roles in maintaining soil quality and fertility due to their involvement in nutrient cycling through decomposition of organic residues, improvement of soil physical processes, and nutrient storage. Cover crops and their residues encourage several faunal activities in the soil. Soil fauna modify soil structure through the formation of micropores and aggregates, thereby improving water infiltration and pore volume (Tian and Badejo, 2001). Aggregate stability is improved through production of extracellular polysaccharides (bacteria and fungi) and physical binding of clay minerals with hyphae (fungi, actinomycetes) (Scow and Werner, 1998). Tian and Badejo (2001) have discussed the roles of earthworms and micro arthropods on soil fertility maintenance (organic matter breakdown, mineralization, aggregation, soil porosity) and their beneficial effects on plant growth and crop yields in West Africa. Cover crops directly

influence soil faunal activities through their root growth, root exudates (amino acids, simple sugars, organic acids), and addition of crop residues. These residues help provide suitable moisture and temperature conditions, as well as energy and mineral nutrients needed by soil organisms.

Soil biochemical processes induced by microbes include increased bioavailability of S, Mn, and Fe. For example, aerobic and facultative anaerobic bacteria produce siderophores (low-molecular-weight Fe^{3+} chelating agents) that improve Fe availability to plants. Cover crops may also increase arbuscular mycorrhizal fungi (AMF) activities (Upadhyaya and Black, 2007). These AMF, in symbiotic association with crop roots, help to absorb P and micronutrients in infertile soils and increase N_2 fixation. They can also increase plant tolerance to soil chemical constraints (acidity, alkalinity, salinity), toxic elements, drought, and resistance to fungal pathogens and parasitic nematodes (Fageria et al., 2005). Cover crops may also increase pesticide degradation in the soil.

19.4.6 Weed Suppression

Weed infestation is one of the major constraints to crop production. Weeds compete for water and nutrients, harbor insect pests and disease pathogens, and intercept insecticides/fungicides, thus reducing their effectiveness. Cover crops suppress and control weed growth in field and plantation crops (Bugg et al., 1991; Teasdale, 1998; Teasdale et al., 2007). In the tropics, jack bean and pigeon peas as summer intercrops reduced weeds by 83%. In temperate region, subterranean clover and white clover grown as summer intercrops reduced weeds by 48% (Teasdale et al., 2007) Weed suppression by cover crops can be due to shading, competition for nutrients and water, and allelopathic interactions (Conklin et al., 2002; Blackshaw et al., 2007). Growing cover crops can compete with weeds for light, nutrients, and water; cover crop residues can shade the soil and inhibit weed seed germination. Warm-season cover crops are very effective when grown in rotation with crops in subtropical and tropical areas in reducing weed populations (Teasdale et al., 2007). Cover crops have their beneficial effects by reducing weed establishment and minimizing weed competition with economic crops (Blackshaw et al., 2007). Inclusion of cover crops in a cropping system can markedly reduce weed populations over time. Best weed control is achieved by having a high density of cover crops and longer growth of cover crop. Butterfly pea, green leaf desmodium, tropical kudzu, cowpea, sunhemp, jack bean, buffalo bean/velvet bean, and sorghum-sudan grass (*Sorghum bicolor* L. × *S. sudanense*, Piper) have successfully suppressed weeds in tropical field crops (Teasdale et al., 2007). Barley silage effectively reduced wild oat densities in the subsequent crops (Harker et al., 2003). Rye (*Secale cereale* L.) hairy vetch (*Vicia villosa* Roth), various clovers (*Trofolium* spp.), and mustard species (*Brassica* spp.) are very effective in controlling weeds in temperate crops (Teasdale et al., 2007). Living or decaying cover crop residues of rye (*Secale cereale*), oats (*Avena sativa*), barley, mustard (*Brassica* spp.), and sweetclovers release allelopathic compounds that are converted by soil microbes into phytotoxic compound that inhibit weeds (Blackshaw et al., 2007; Teasdale et al., 2007). Cover crops such as mucuna, calapo, sunhemp, and jack bean are very effective in suppressing the growth of perennial weeds such as cogongrass (*Imperata cylindrica* L. Beauv), bermudagrass (*Cynodon dactylon* L. Pers), and sedges (*Cyperus* spp.), where as tropical kadzu, velvet bean, and cowpeas have the potential to control parasitic weeds such as witchweed (*Striga asiatica* L. Ktze) (Teasdale et al., 2007).

Combining appropriate management practices (tillage, crop rotation, intercropping, mowing, and herbicides) with cover crops can suppress weeds more effectively than cover crops alone (Blackshaw et al., 2007; Teasdale et al., 2007). However, use of cover crops can reduce the amount and costs of tillage and herbicide application.

19.4.7 Reduction of Diseases and Insect Pest Problems

Pests and diseases greatly limit crop yields and quality. Chemicals (fungicides, bactericides, nematicides, insecticides) are the primary measures used to control diseases and insects, but they increase the costs of production and can lead to environmental degradation. Increased organic matter added

to soil by cover crops stimulates beneficial soil flora and fauna that can reduce some soil borne diseases, nematodes, and insects. Cover crops harbor many beneficial predatory insects that serve as biological control agents.

Brassica species produce glucosinolate-containing crop residues (2–6 Mg ha^{-1}) that can suppress plant parasitic nematodes and soil born diseases (Porter et al., 1998; Lazzeri and Manici, 2001; Snapp et al., 2005). Incorporation of a short alfalfa rotation reduced *Rhizoctonia solani* infection in potato by 50% (Honeycutt et al., 1996). Lazarus and White (1984) described chemical use reduction through the integration of a rye cover crop into a range of cropping systems, including potato, cauliflower, sugarbeet, and dry bean.

19.4.8 Crop Yield Improvements

Cover crops improve soil physical, chemical, and biological properties, and these in turn can increase crop yields. Tropical kadzu can improve nutrient availability, control soil erosion, stimulate biological activities, and increase crop yields. During the establishment phase of tropical plantation crops, butterfly pea, calapo, crotolaria, sesbania, flemingia, tropical kadzu, and white tephrosia cover crops are effective in controlling weeds, reducing soil erosion, and improving plantation growth. However, as the plantation trees grow, the effectiveness of cover crops may decline due low solar radiation penetrating the tree cover. Temperate cover crops improve crop yields by improving soil characteristics by speeding infiltration, reducing waterlogging, improving aeration, reducing soil compaction, and encouraging beneficial soil microbes that enhance nutrient cycling (Clark, 2007).

19.5 STRENGTHS AND LIMITATIONS

Fast growth and the ability to cover the soil rapidly are traits of cover crops that help control soil erosion (Skerman et al., 1988). Strengths and limitations of tropical and temperate cover crops are summarized in Tables 19.10 and 19.11, respectively. Tolerance to low soil fertility, soil acidity, flooding, pests, and diseases, as well as the ability to fix atmospheric N_2 and reduce soil erosion, are characteristics needed in cover crops (Ingels et al., 1998).

Wood and Lass (2001) list the disadvantages of cover crops in tropical plantation crops as follows. They are difficult and expensive to establish; they may be ineffective or, alternatively, too effective at covering the soil; and they may suffer from or encourage pests and diseases. Cover crops may also deplete soil moisture and nutrients, may pose problems as weeds, or attract arthropods or rodents (Fageria et al., 2005). Cover crop residues with C/N ratio above 25 may immobilize soil N. Some cover crops control plant parasitic nematodes, but others have been reported to increase them. Nevertheless, most of these negative effects of cover crops are uncommon and are usually balanced by positive effects.

19.6 MANAGEMENT AND FERTILIZER REQUIREMENTS

Many tropical soils under cover crops are acidic with Al and Mn toxicities and are low in essential nutrients such as P, N, Zn, Fe, and Cu. Lime addition to acid soils reduces toxicities of Al and Mn, improves the availabilities of Ca, Mg, P and Mo and N_2 fixation, and reduces the availability of Mn, Zn, Cu, and Fe (Baligar and Fageria, 1999). Managing soil pH is essential to achieve good cover crop establishment and growth.

Recommended seeding rates and fertilizer requirements of various cover crops are given in Tables 19.12 and 19.13 (Duke, 1981; Skerman et al., 1988; FAO, 2007; Cook et al., 2005; Baligar and Fageria, 2007; Clark, 2007). Well-nodulated leguminous cover crops often respond to small amounts of fertilizer N, and on infertile soils, application of N and P fertilizers can improve their persistence, yield, and shade tolerance. Deficiency of Mo, Cu, and Zn has been reported in many tropical cover crops, and they often respond well to applied P, K, Cu, Mo, and Zn (Bruce, 1978; Skerman et al., 1988; Tian et al., 1998). As with other crops, fertilizer and lime should be applied based on the soil test.

TABLE 19.10
Strengths and Limitations of Tropical Cover Crops

Common Name	Strength	Limitation
Velvet bean	Fast growing, easy to produce, improves soil fertility and yield, resistant to many pests and diseases	Constrained by low P and high acidity, limited drought tolerance, susceptible to waterlogging, toxic to monogastric animal
Butterfly pea	Efficient N fixation (up to 520 kg/ha), persists under shade, cool-season growth Stoloniferous growth habit	Slow to establish, problems with *Cercospora* leaf spot and spider mites, limited to low elevations
Calopo	Wide edaphic adaption, establishes rapidly Good tolerance to extreme conditions	Poor tolerance of heavy shade, some weed potential Susceptible to root-knot nematode and cowpea viruses
Centro	Adapts to very acid, low-fertility soils, good drought tolerance, high nutritive value, tolerant of many diseases	Low persistence when mixed with grasses, low seed production
Cowpea	Multi-purpose: leaf, grain, forage, improves soil fertility, ease of establishment, adaptation to a wide range of soils, drought and heat tolerant, high seed production	Many pests and diseases of beans
Showy crotalaria	Rapid development, control of root-knot nematodes, requires little attention after established, reduces nematodes numbers	Toxicity to animals, high potential as a weed
Smooth crotalaria	Good green manure crop, reduces nematodes numbers	Pest and disease problems Susceptible to root-knot nematode Toxic to animals
Sunn hemp	Fast-growing species, very effective in smothering weeds, drought tolerant, reduces population of many parasitic nematodes	Not tolerant of salt or frost, wide range of diseases and nematodes
Ea-Ea	Well adapted to acid, infertile soils, good for restoring degraded soils, good shade tolerance	Poor drought tolerance, susceptible to false rust (*Synchytrium desmodii*), foliar blight (*Rhizoctonia solani*) and root-knot nematodes (*Meloidogyne javanica*)
Flemingia	Adapted to acid, infertile soils, drought and shade tolerant, reduces nematodes Slow breakdown as mulch	Slow to establish, potential as a weed Host of the pigeon pea pod fly (*Melanagromyza obtuse*)
Hairy indigo	Strong ability to reseed, reduces nematodes Tolerates most diseases and pests	Slow to establish, high weed potential
Jack bean	Drought tolerant, good erosion control, reduces nematodes numbers	Host many fungi and pests
Joint-vetch	Grows in low-lying, wet areas, tolerates low fertility, high N fixation, high nutritive value	Slow to establish, not very tolerant of shade Susceptibility to botrytis and powdery mildew, attacked by corn earworm (*Helicoverpa armigera*)
Perennial peanut	Tolerant of low fertility, productive, high quality pasture, good ground cover Combines with sward grasses, few diseases	Slow and costly to establish, needs good moisture Underground seeds attract rodents, difficult to eradicate, susceptible to root-lesion nematodes and spider mites

(*continued*)

TABLE 19.10 (continued)
Strengths and Limitations of Tropical Cover Crops

Common Name	Strength	Limitation
Sesbania	Rapid establishment and growth, tolerant of acid-soil, waterlogging, salinity, and shade, few pests	Short-lived (1–5 years), not tolerant of drought Low palatability to young animals, specific cutting management
Brazilian lucerne	Adapted to acid, infertile soils, low P requirement, tolerant of Al and Mn Easily established from seed or cuttings High N fixation	Requires very specific Rhizobium, can reduce yield of subsequent crops, seed tends to shatter on ripening Susceptible to Anthracnose (*Colletotrichum gloeosporioides*)
Stylo, capitata	Tolerant of low fertility, productive, high quality, combines well with grasses	Limited to very acid soils, high weed potential Susceptible to Anthracnose (*Colletotrichum gloeosporioides*)
Stylo, macrocephala	Adapted to low fertility, tolerates high Al and Mn, moderately productive, good quality	Limited to very acid soils, may invade cultivated land
Vogel's tephrosia	Good N fixation, good green manure crop Hedge crop in citrus, rubber, cinnamon Tolerant of drought	Toxic to fish, susceptible to root-knot nematode and Helopeltis (pest of cocoa) Not as promising as *T. candida*
White tephrosia	Grows on poor acid soils, good N fixation Excellent erosion control, cover crop for coffee, rubber, tea	Toxic to fish, susceptible to nematodes
Tropical kudzu	Vigorous initial growth, suppresses weeds No severe pests or diseases, drought tolerant	Tends to climb trees, not tolerant of dense shade Low persistence under grazing, susceptible to leaf eating caterpillars
Cowpea	Moderately tolerant to drought	Not tolerant to water logging
Pigeon pea	Very heat tolerant, good N_2 fixer, drought tolerant	It is sensitive to salinity and water logging
Mung bean	Adapted to warm climate, tolerant to drought. Tolerate heat	High nutrient requirement
Moth bean	Good cover crops for aarid and semiarid tropics	Weed infestation in early growth
Guar	Low soil fertility requirement. Tolerant to drought. Moderate to high potentials for N_2 fixation and Moderate to low potential for erosion control. Resistant to Meloidogyne spp.	Water stress, diseases and weeds affect its production. Susceptible to water logging. Need seed scarification
Annual peanut	Tolerant to drought. Moderate to low potentials for N_2 fixation and erosion control. Shade intolerant	Susceptible to water logging. Drought, diseases and insects are the main yield limiting factors
Lablab bean	Low soil fertility requirement. Tolerant to drought High to moderate potential for N_2 fixation and soil erosion control	Susceptible to water logging Need seed scarification
Tepary bean	Low soil fertility requirement. Tolerant to drought. High to low potential for N_2 fixation and soil erosion control	Susceptible to water logging
Lima bean	Moderately tolerant to drought. Low soil fertility requirement. High to low potential for N_2 fixation and soil erosion control	Susceptible to water logging. More susceptible to insect attack at flowering and highly susceptible to Meloidogyne spp.
Egyptian clover	Requires moderate soil fertility Tolerant to drought. Moderately tolerant to water High potential for N_2 fixation logging High to moderate potential for N_2 fixation	Diseases and insect are major yield limiting factors

TABLE 19.10 (continued)
Strengths and Limitations of Tropical Cover Crops

Common Name	Strength	Limitation
Adzuki bean	Moderate soil fertility requirement. Tolerant to drought	Susceptible to water logging. Moderate to low N_2 fixation and soil erosion control
Rice bean	Moderate soil fertility requirement. Tolerant to drought	Susceptible to water logging. Moderate to low N_2 fixation and soil erosion control
Sesbania	Well suited as green manure crop	Not tolerant to frost, susceptible to nematodes
Perlmillet	Tolerate waterlogging, moderately tolerant to salinity, drought resistance	Water deficit, nutrient deficiency, weeds and diseases are common yield limiting factors
Sorghum	Tolerate low soil fertility, moderately tolerant to water logging. Tolerant to drought	None or minor soil control properties

Sources: Duke, J.A., *Handbook of Legumes of World Economic Importance*, Plenum Press, New York, 1981; Skerman, P.J. et al., (eds.), *Tropical Forage Legumes*, FAO-United Nations, Rome, Italy, 1988; Van der Maesen, L.J.G. and Somaatmadja, S., (eds.), *Plant Resources of South-East Asia, No. 1, Pulses*, Pudoc, Wageningen, the Netherlands, 1989; Faridah Hanum, I. and van der Maesen, L.J.G., (eds.), *Plant Resources of South-East Asia, No. 11, Auxiliary Plants*, Backhuys Publishers, Leiden, the Netherlands, 1997; LEXSYS, *Decision Support for the Selection of Legumes for Incorporation into Tropical Cropping Systems*, International Institute of Tropical Agriculture, Ibadan, Nigeria and the School of Environment and Natural Resources, University of Wales, Bangor, U.K., 2003; Cook, B.G. et al., Tropical forages: An interactive selection tool, 2005, available at http://www.tropicalforages.info/key/Forages/Media/Html/index.htm, accessed October 20, 2006; Lewis, G.B. et al., (eds.), *Legumes of the World*, Kew Publishing, Richmond, Surrey, U.K., 2005; Roskov, Y.R. et al., (eds.) ILDIS legume web, 2005, available at http://www.ildis.org/, accessed November 6, 2006; USDA-ARS, Germplasm resources information network (GRIN), 2006, available at http://www.ars-grin.gov/cgi-bin/npgs/html/tax_search.pl, accessed November 8, 2006; FAO, Grassland species database, 2007, available at http://www.fao.org/AG/AGp/agpc/doc/Gbase/Default.htm, accessed January 5, 2007; Baligar, V.C. and Fageria, N.K., *J. Plant Nutr.*, 30, 1287, 2007.

19.7 STRATEGIES FOR SUCCESS IN COVER CROP ESTABLISHMENT

Obtaining benefits from cover crops requires selection of suitable species, seed treatment to improve germination, seed inoculation with appropriate rhizobia, good land preparation and plant spacing, adequate light interception, and management of crop residues and drought. These strategies are briefly discussed in the following sections.

19.7.1 Suitability of Species

Selection of an appropriate cover crop depends on the nature of main crops (row or plantation crop), growth stage of the plantation (new or established), and the objectives of establishing the cover crop (soil erosion control, weed control, reducing pests and diseases, improving soil fertility, lowering costs of production). Well-adapted cover crops should be adapted to the local climate and soils, germinate well in relatively dry soil, grow quickly, and cover the soil rapidly to prevent soil erosion, be good scavengers of nutrients, and produce large amounts of residue, thereby improving SOM and suppressing weeds (Clark, 2007).

19.7.2 Seed Treatment

Many cover crop, particularly those used in tropics, have 60%–90% hard seeds that require treatment to increase germination. Recommended treatments include scarifying mechanically with a rice polisher or sand, treatment with concentrated sulfuric acid, heat treatment with warm water, or treating with 20% NaOH (Skerman et al., 1988).

TABLE 19.11
Strengths and Limitations of Temperate Cover Crops

Common Name	Strength	Limitations
	Legume	
Hairy vetch	Great source of N, weed suppresser, reduce erosion, soil conditioner and reduce water runoff. Improve surface soil tilth	Host numerous small insects and southern corn root worms. Increases Soybean cyst nematode and root-knot nematode
Alfalfa	Low soil fertility requirement. Moderately tolerant to water logging, tolerant to drought High to moderate N_2 fixation and soil erosion control, great source of N, soil builder, weed fighter	Need seed scarification
Red clover	Great source of N, soil builder, weed suppresser, attracts beneficial insects	Susceptible to root rots and foliar diseases
Kura clover	Forage for grazing. Very cold hardy, best on well drained fertile soils, resistant to drought	High percentage of hard seeds. During drought goes dormant, susceptible to powdery mildew
Ladino clover	Tolerates moderate drought, soil improver	Not suitable to acid and ill-drained soils. 30%–40% hard seed, host pest and diseases
Subterranean clover	Low soil fertility requirement. High to moderate N_2 fixation and soil erosion control Resistant to Meloidogyne, great source of N, soil builder, subsoil loosener, weed fighter, erosion suppressor, self seeder	Susceptible to water logging and drought, susceptible to *Lygus lineolaris* bugs, little resistance to root-knot nematodes
Faba bean	Low soil fertility requirement. Moderately tolerant to water logging High to low N_2 fixation. Moderate to low potential for soil erosion control	Susceptibly to diseases. Susceptible to drought
Winter pea	Great source of N, winter tolerant	Seed viability is short lived
Milk vetch	Tolerant to waterlogging	Donot sustains prolonged flooding
Berseem clover	Great source of N, weed fighter, prevents erosion	Least winter hardy, allelopathic effects on succeeding crops, lygus bug infection, susceptible to Meloidogyne
Cowpeas	Low soil fertility requirement. Tolerant to drought. Moderate to low N_2 fixation. High to low potential for soil erosion control, erosion fighter, weed fighter, heat tolerant, r	Susceptible to water logging susceptible to diseases and insect attack, susceptible to root rot
Crimson clover	Great source of N, pest fighter, soil builder, erosion preventer	Secondary host to corn ear worm and cotton bollworm (*Heliothu* spp) pest
Field peas	Good N source, weed suppresser, winter hardy	Susceptible to crown rot (*clerotinia*), susceptible to crown rot, root rot, blight. Host some races of nematodes
Sweet clover	Great source of N, soil builder, subsoil aerator, weed suppressor, erosion preventer, reduces sub soil compaction	Sweet clover weevil is major pest
White clover	Tolerate wet soils and short floods and dry spells, erosion preventer, attracts beneficial insects, fairly tolerant to nematodes	Susceptible to root and stolen rots. Leaf hopper, meadow spittlebugs, clover leaf weevil, alfaala weevil and Lygus bugs
Woollypod vetch	Low soil fertility requirement, moderately tolerant to drought, high to moderate N_2 fixation and soil erosion control, weed fighter	Susceptible to waterlogging, hard seed carry over could become weeds, climbing habits could suppress grape growth, host to *Sclerotinia minor* soil borne pathogen

TABLE 19.11 (continued)
Strengths and Limitations of Temperate Cover Crops

Common Name	Strength	Limitations
	Nonlegume	
Annual ryegrass	Soil builder, erosion fighter, weed fighter, improves soil structure, suppress weeds, help to reduce insect pests	It can become weed, brown and crown rust, host pin nematodes, and broom grass mosaic virus
Barley	Soil builder, erosion fighter, weed fighter, improves soil structure, suppress weeds, reduce root not (Meloidogyne) nematodes	Allelopathic to subsequent crops
Oats	Erosion fighter, weed fighter, nutrient scavenger help to reduce root not nematodes, tolerant to wet soil	Allelopathic to subsequent crops
Rye	Soil builder, weed fighter, pest fighter, suppress weeds, cold and drought tolerant	Allelopathic to subsequent crops
Wheat	Weed fighter, prevent erosion, scavenge excess nutrients	Suceptible to insects and diseases, builds up pathogens
Buck wheat	Weed fighter, quick soil cover, top soil loosner	Not drought tolerant, leaf spot is major disease
Sorghum-sudan grass	Soil builder, erosion fighter, subsoil loosener, weed and nematode suppressor, pest fighter, helps to control nutsedge infestation, controls nematode infestation	Chinch bug corn leaf aphid, corn ear worm, green bugs are major pests
Brassica and mustard	Prevent erosion, supree weeds and soil borne pest, alleviate soil compaction and scavenge nutrient	Host to parasitic nematodes

Sources: LEXSYS, *Decision Support for the Selection of Legumes for Incorporation into Tropical Cropping Systems*, International Institute of Tropical Agriculture, Ibadan, Nigeria and the School of Environment and Natural Resources, University of Wales, Bangor, U.K., 2003; Clark, A. (ed.). *Managing Cover Crops Profitably* (Sustainable Agricultural Network Handbook Series Book 9), 3rd edn., Scientific Agricultural Network, Beltsville, MD, 2007; Baligar, V.C. and Fageria, N.K., *J. Plant Nutr.*, 30, 1287, 2007.

19.7.3 Seed Inoculation with Rhizobia and Mycorrhizae

Bacteria responsible for N fixation in leguminous cover crops include *Rhizobium* and *Bradyrhizobium* species. Legumes are highly specific in their *Rhizobium* requirements, and inoculation with an appropriate strain of N_2-fixing bacteria can greatly improve N_2 fixation. Poor performance of cover crops may be due to poor nodulation and N_2 fixation. Soils contain numerous strains of rhizobia, but they are often ineffective N_2 fixers.

Arbuscular mycorrhizae fungi (AMF) also form symbiotic associations with roots and enhance water and nutrient uptake, as well as early growth and survivability. Mycorrhiza especially promotes effective uptake of P and micronutrients by plants. Seed inoculations are known to improve nutrient uptake efficiency, tolerance to soil chemical constraints, and drought resistance (Marschner, 1995).

19.7.4 Land Preparation and Planting

As is the case with other crops, good land preparation (tillage, addition of starter fertilizers), and planting methods (drilling, broadcast, planted rooted cuttings) are vital for establishment of cover crops. Spacing, seeding rates, and fertilizer needed to achieve maximum effective establishment of various cover crops are shown in Tables 19.12 through 19.14. Sowing appropriate rates of good

TABLE 19.12
Management Tropical Cover Crops Useful to Plantation Crops

Common Name	Spacing		Seeding Rate (kg/ha)	Hard Seed	Fertilizer Needed
	Row (cm)	Within Row (cm)			
Velvet bean	25–180	15–90	10–80		Responds to P (50–225 kg/ha superphosphate) and lime applications
Butterfly pea	20–100	50	4–8	60%	P 10 kg/ha, dolomitic limestone 1 t/ha
Calopo	Broadcast		1–3	75%	P 20, S 20, K 60 kg/ha, 1 t/ha dolomitic limestone
Centro					
Cowpea	40–90	5–50	10–40		Responds to P, K, S, Ca, and Mo applications
Showy crotalaria	25–50	5–7	6–34		
Smooth crotalaria	25–50	5–7	10–20		
Sunn hemp	Broadcast		25–96		
Ea-Ea	Broadcast		1–2		Responds to lime 500 kg/ha, P, Mg, S 20 kg/ha and B
Flemingia	80–90	10–20		High	None needed
Hairy indigo	Broadcast		3–10		30–70 kg/ha of P and K
Jack bean	60–75	45–60	25–100		
Joint vetch	Broadcast		2–6	90%	P 20 kg/ha at establishment, 200 g/ha Mo every few years
Perennial peanut			10–30		P 20, Ca 100, K 20, Mg 14, S 22 kg/ha at establishment
Sesbania	200–1000	25–50	20–60	High	Responds to added P
Brazilian lucerne	30–60		2–5	70%	P 20, K 20, Ca 100, Mg 14, S 22 kg/ha
Stylo, capitata	Broadcast		2–5	High	In deficient soils, 10–20 kg/ha P recommended
Stylo, macrocephala			4–5	High	Response to P varies with genotype
Vogel's tephrosia	40–50	40	5–13		
White tephrosia	Broadcast		3–20	High	Responds well to fertilizers
Tropical kudzu	80–600	100	1–8	95%	Susceptible to Mg and S deficiencies, low Ca and P requirements

Sources: Duke, J.A., *Handbook of Legumes of World Economic Importance*, Plenum Press, New York, 1981; Skerman, P.J. et al., (eds.), *Tropical Forage Legumes*, FAO-United Nations, Rome, Italy, 1988; Van der Maesen, L.J.G. and Somaatmadja, S., (eds.), *Plant Resources of South-East Asia, No. 1, Pulses*, Pudoc, Wageningen, the Netherlands, 1989; Faridah Hanum, I. and van der Maesen, L.J.G., (eds.), *Plant Resources of South-East Asia, No. 11, Auxiliary Plants*, Backhuys Publishers, Leiden, the Netherlands, 1997; LEXSYS, *Decision Support for the Selection of Legumes for Incorporation into Tropical Cropping Systems*, International Institute of Tropical Agriculture, Ibadan, Nigeria and the School of Environment and Natural Resources, University of Wales, Bangor, U.K., 2003; Cook, B.G. et al., Tropical forages: An interactive selection tool, 2005, available at http://www.tropicalforages.info/key/Forages/Media/Html/index.htm, accessed October 20, 2006; Lewis, G.B. et al., (eds.), *Legumes of the World*, Kew Publishing, Richmond, Surrey, U.K., 2005; Roskov, Y.R. et al., (eds.), ILDIS legume web, 2005, available at http://www.ildis.org/, accessed November 6, 2006; USDA-ARS, Germplasm resources information network (GRIN), 2006, available at http://www.ars-grin.gov/cgi-bin/npgs/html/tax_search.pl, accessed November 8, 2006; FAO, Grassland species database, 2007, available at http://www.fao.org/AG/AGp/agpc/doc/Gbase/Default.htm, accessed January 5, 2007.

TABLE 19.13
Management Tropical Cover Crops Useful to Row Crops

	Seeding Rates (kg ha^{-1})		
Common Name	**Drilled**	**Broadcast**	**Fertilizer Need (kg ha^{-1})**
Cowpea	10–40	90	Mostly no fertilizer, small amount of P and K added
Pigeon pea	0.5–4		Mostly no fertilizer, small amount of P and K added 20–25 N and 17–26 P
Mung bean			20 N, 13–20 P, 25–40 K
Moth bean			Mostly no fertilizer, small amount of P and K added
Guar			20–3-P
Annual peanut			Adequate supply of N, P, K
Lablab bean	12–20		Mostly no fertilizer, small
Tepary bean			30 N, 30 P, 30 K
Lima bean			30–40 P, 20–30 K
Black gram			30–40 P, 20–30 K
Egyptian clover			40 P, 80 K, 2.5–5.0 Mg
Adzuki bean			20 N, 60 P, 50 K
Rice bean			30–04 P, 25–30 K
Sesbania			30 P, 20 K
Perlmillet	5–15	25–30	40–100 N, 20–60 P, 40–21 K
Sorghum	4–10	20	30–50 N, 10 P, 50 K

Source: Baligar, V.C. and Fageria, N.K., *J. Plant Nutr.*, 30, 1287, 2007.

quality seeds, removal of weeds, and (if needed) addition of lime and starter fertilizers are prerequisites for successful cover crop establishment.

19.7.5 Light and Shade Management

The amount of light reaching the cover crop canopy is an important factor that can limit its growth, development and persistence, especially in plantation systems, where a taller established crop may shade out the young cover crop. Use of cover crops to control weeds and reduce the use of herbicides has increased interest in finding shade tolerant cover crops. In tropical plantation crops, Ea-Ea and butterfly pea are very shade-tolerant and buffalo bean, Calapo, Flemingina, Jack bean, Centro, cowpea, hairy indigo, joint vetch, jack bean, perennial peanut, susbania, tropical kadzu, and white tephrosia are moderately tolerant to shade (LEXSYS, 2003). In temperate cover crops, annual ryegrass, rye, Berseem clover, Crimson clover, Medic and white clover have shown shade tolerance (Clark, 2007).

19.7.6 Crop Residue Management

Cover crops annually produce a substantial amount of dry matter that is converted into crop residues, which is either incorporated into the soil or left as surface, as mulch can reduce soil erosion and N losses. Excess residue accumulation and slow decomposition can lead to immobilization of N under temperate conditions. However, under subtropical and tropical conditions, high temperatures cause crop residues to decompose rapidly. Organic matter added to the soil as crop residue can improve nutrient cycling and reduce nutrient losses to as runoff and deep percolation. Crop residues increase soil faunal and microbial activities, thereby increasing nutrient cycling and enhancing nutrient availability to cover crops and main crops.

Microbial biomass and activity in soil is an indicator of C turnover and availability from organic residues (Tian et al., 1992). The composition of organic residues determines their influence on microbial activity and soil aggregation (Lynch and Bragg, 1985). Grant et al. (2002) reported that

TABLE 19.14
Management of Temperate Cover Crops

	Seeding Rates	
Common Name	**Drilled (kg ha^{-1})**	**Broadcast (kg ha^{-1})**
Hairy vetch	17–22	28–55
Alfala	9–25	13–29
Red clover	9–12	12–13
Kura clover	12–15	
Ladino clover	2–5	
Subterranean clover	12–22	22–34
Berseem clover	9–13	17–22
Cowpeas	34–100	78–134
Crimson clover	17–22	25–34
Field peas	56–90	100–112
Red clover	9–12	12–13
Sweet clover	7–12	12–22
White clover	4–10	6–16
Woollypod vetch	13–34	36–87
Nonlegume		
Annual ryegrass	11–22	22–34
Barley	56–112	89–140
Oats	90–123	123–157
Rye	67–134	100–179
Wheat	67–134	67–168
Buck wheat	54–78	56–100
Sorghum-sudan grass	39	45–56

Sources: Clark, A. (ed.), *Managing Cover Crops Profitably* (Sustainable Agricultural Network Handbook Series Book 9), 3rd edn., Scientific Agricultural Network, Beltsville, MD, 2007; Ingels, C.A. et al., (eds.), *Cover Cropping in Vineyards: A Growers Handbook*. Publication No. 3338. Division of Agricultural and Natural Resource, University of California, Oakland, CA, 1998.

the N concentration of crop residues determines the net balance between mineralization and immobilization. If the N concentration in the residue is below approximately 20–24 g N kg^{-1} dry matter, immobilization will exceed mineralization, and the decomposition residues will immobilize N rather than release it (Fageria, 2007). When plant residues have C/N ratios greater than 20, available soil N is immobilized during the first few weeks of decomposition. A residue C/N ratios less than 20 results in net N mineralization (Doran and Smith, 1991; Fageria, 2007).

Over the longer term, the N fertilization equivalent of above ground wheat and barley residues, with C/N ratios above 80, is only around 12 kg N ha^{-1}, or about 9%–11% (Fredickson et al., 1982; Delegado et al., 2004). Typical C/N ratios of several important crops are presented in Table 19.15, clearly demonstrating that legumes normally have lower C/N ratios than cereals.

Cover crops have many well-recognized advantages; however, concern has been raised that cover crop may create N deficiencies in the next crop if too much N is immobilized and not released in a timely manner (Vyn et al., 1999). Karlen and Doran (1991) showed that cover crops before corn created an early-season N deficiency in the corn, and even additional N fertilizer did not make up the

TABLE 19.15
C/N Ratio of Major Legume and Cereal Cover Crops

Crop Species	Growth Stage/Age in Days	C/N Ratio
Corn residues (*Zea mays* L.)	Physiological maturity	67
Rice straw (*Oryza sativa* L.)	Physiological maturity	69
Rice straw (*Oryza sativa* L.)	Physiological maturity	56
Sorghum (*Sorghum bicolor* L. Moench)	Vegetative	22.0
Barley straw (*Hordeum vulgare* L.)	Physiological maturity	99.1
Ryegrass (*Lolium multiflorum* Lam)	Vegetative	30
Rye (*Secale cereale* L.)	Heading	40
Alfalfa hay (*Medicago sativa* L.)	Not given	15.9
Pea straw (*Pisum sativum* L.)	Physiological maturity	21
Pea hay (*Pisum sativum* L.)	Not given	15.4
Red clover (*Trifolium pratense* L.)	101 days	13.7
White clover (*Trifolium repens* L.)	101 days	10.7
Yellow trefoil (*Medicago lupulina* L.)	101 days	10.1
Persian clover (*Trifolium resupinatum* L.)	101 days	15.8
Egyptian clover (*Trifolium alexandrium* L.)	101 days	16.7
Subterranean clover (*T. subterraneum* L.)	101 days	11.4
Cowpea (*Vigna unguiculata* L. Walp.)	Green pods	13.9
Sunn hemp (*Crotalaria juncea* L.)	Mature pods	20.2
Soybean (*Glycine max* L. Merr.)	Vegetative	17.9
Pigeon pea (*Cajanus cajan* L. Millspaugh)	Not given	25.9
Wild indigo (*Indigofera tinctoria* L.)	Flowering	15.8
Sesbania (*Sesbania rostrata* Bremek & Oberm)	Vegetative	27.8
Sesbania (*Sesbania emerus* Aubl. Urb.)	Vegetative	26.5
Aeschynomene afraspera	Vegetative	23.9
Desmanthus virgatus	Green pods	18.9
Tropical kudzu (*Pueraria phaseoloides*)	Not given	19
Hairy vetch (*Vicia villosa* Roth)	Vegetative	12
Hairy vetch (*Vicia villosa* Roth)	Flowering	18
Hairy vetch (*Vicia villosa* Roth)	Early bloom	17
Crimson clover (*Trifolium incarnatum* L.)	Midbloom	11

Source: Adapted from Fageria, N.K., *J. Plant Nutr.*, 5, 691, 2007.

difference. Similarly, Martinez and Guiraud (1990), Francis et al. (1998), and Wyland et al. (1995) reported that cover crops with high C/N ratios may reduce yields of succeeding cash crops because of N immobilization. It is often stated that net N immobilization is likely to occur following addition of plant material with a C/N ratio above 25 (Fageria et al., 2005).

Other studies have shown that a rye cover crop may reduce subsequent corn yields because of allelopathic effects (Raimbault et al., 1990), or N immobilization under low N conditions (Ebelhar et al., 1984; Blevins et al., 1990). Further research may identify rye genotypes that do not release these compounds (Dinnes et al., 2002).

19.7.7 Drought Management

The cost of seeding is a major expense; therefore, obtaining an adequate stand is very critical. Selection of species and cultivars within species that are well adapted to the regional climatic conditions is important. Drought during germination is very detrimental to cover crop establishment; therefore,

planting should occur when weather conditions permit good germination and establishment. Cover crops have various degrees of tolerance to drought. Centro, jack bean, Brazilian lucerne, sunhemp, Vogel's tephrosia, and tropical kudzu are classified as drought tolerant. In contrast, velvet bean and calapo have little tolerance to drought.

Rye has been used successfully as a cover crop in the northern U.S. corn and soybean belt (Dinnes et al., 2002). However, rye should not be grown to maturity as a cover crop because it can reduce the yield of subsequent crops by using too much water in the spring or immobilizing large amounts of soil N (Tollenaar et al., 1993). Thelen et al. (2004) reported that moisture stress from the interseeded rye was a predominate factor in soybean grain yield reduction.

19.8 SUMMARY

Cover crops are important components of cropping systems to sustain productivity of crops without degrading the environment. The positive effects of cover crops in improving soil fertility have been known since ancient times. Cover crops have received additional interest in recent years because of the high cost of chemical fertilizers, increased risk of environmental pollution, and the need to use sustainable cropping systems. Cover crops can be planted in rotation with annual cash crops or in association with plantation crops like cacao, coffee, banana, rubber, and oil palm. Their use cropping systems usually improves soil and water conservation, recycling of nutrients, and control of pests. However, beneficial effects depend on the selection of adapted cover crops and their proper management. Hence, understanding cover crop agronomy and physiology is fundamental to their successful use in sustainable cropping systems.

Desirable attributes of a cover crop include the ability to establish rapidly under less than ideal conditions, provide sufficient dry matter and soil cover, fix atmospheric N_2, establish a deep root system to facilitate nutrient uptake from lower soil depths, produce organic matter with low residue C/N ratios, and absence of phytoxic or allelopathic effects on subsequent crops. Cover crops can be leguminous or nonleguminous. Leguminous cover crops can provide a substantial amount of biologically fixed N to the primary crop. Legume cover crops can also absorb nutrients from deep in the soil profile and can help in increasing the concentration of plant nutrients in the surface layers of soil. Some grass cover crops can scavenge more mineral N from the soil profile than leguminous cover crops, and growing mixtures of grasses and legumes appears to be the best strategy in obtaining maximum N cycling benefits from cover crops.

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