# 1 Introduction

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## 1.1 DEFINITIONS

### 1.1.1 PLANT NUTRIENT

A *plant nutrient* is a chemical element that is essential for plant growth and reproduction. *Essential element* is a term often used to identify a plant nutrient. The term *nutrient* implies essentiality, so it is redundant to call these elements essential nutrients. Commonly, for an element to be a nutrient, it must fit certain criteria. The principal criterion is that the element must be required for a plant to complete its life cycle. The second criterion is that no other element substitutes fully for the element being considered as a nutrient. The third criterion is that all plants require the element. All the elements that have been identified as plant nutrients, however, do not fully meet these criteria, so, some debate occurs regarding the standards for classifying an element as a plant nutrient. Issues related to the identification of new nutrients are addressed in some of the chapters in this handbook.

The first criterion, that the element is essential for a plant to complete its life cycle, has historically been the one with which essentiality is established (1). This criterion includes the property that the element has a direct effect on plant growth and reproduction. In the absence of the essential element or with severe deficiency, the plant will die before it completes the cycle from seed to seed. This requirement acknowledges that the element has a function in plant metabolism; that with short supply of the nutrient, abnormal growth or symptoms of deficiency will develop as a result of the disrupted metabolism; and that the plant may be able to complete its life cycle with restricted growth and abnormal appearance. This criterion also notes that the occurrence of an element in a plant is not evidence of essentiality. Plants will accumulate elements that are in solution without regard to the elements having any essential role in plant metabolism or physiology.

The second criterion states that the role of the element must be unique in plant metabolism or physiology, meaning that no other element will substitute fully for this function. A partial substitution might be possible. For example, a substitution of manganese for magnesium in enzymatic reactions may occur, but no other element will substitute for magnesium in its role as a constituent of chlorophyll (2). Some scientists believe that this criterion is included in the context of the first criterion (3).

The third criterion requires that the essentiality is universal among plants. Elements can affect plant growth without being considered as essential elements (3,4). Enhancement of growth is not a defining characteristic of a plant nutrient, since although growth might be stimulated by an element, the element is not absolutely required for the plant to complete its life cycle. Some plants may respond to certain elements by exhibiting enhanced growth or higher yields, such as that which occurs with the supply of sodium to some crops (5,6). Also, some elements may appear to be required by some plants because the elements have functions in metabolic processes in the plants, such as in the case of cobalt being required for nitrogen-fixing plants (7). Nitrogen fixation, however, is not vital for these plants since they will grow well on mineral or inorganic supplies of nitrogen. Also, plants that do not fix nitrogen do not have any known need for cobalt (3). Elements that might enhance growth or that have a function in some plants but not in all plants are referred to as *beneficial elements*.

Seventeen elements are considered to have met the criteria for designation as plant nutrients. Carbon, hydrogen, and oxygen are derived from air or water. The other 14 are obtained from soil or nutrient solutions (Table 1.1). It is difficult to assign a precise date or a specific researcher to the discovery of the essentiality of an element. For all the nutrients, their roles in agriculture were the subjects of careful investigations long before the elements were accepted as nutrients. Many

**TABLE 1.1**
**Listing of Essential Elements, Their Date of Acceptance as Essential, and Discoverers of Essentiality**

| Element | Date of Essentiality[a] | Researcher[a] |
|---|---|---|
| Nitrogen | 1804 | de Saussure[b] |
| | 1851–1855 | Boussingault[b] |
| Phosphorus | 1839 | Liebig[c] |
| | 1861 | Ville[b] |
| Potassium | 1866 | Birner & Lucanus[b] |
| Calcium | 1862 | Stohmann[b] |
| Magnesium | 1875 | Boehm[b] |
| Sulfur | 1866 | Birner & Lucanus[b] |
| Iron | 1843 | Gris[c] |
| Manganese | 1922 | McHargue[c] |
| Copper | 1925 | McHargue[c] |
| Boron | 1926 | Sommer & Lipman[c] |
| Zinc | 1926 | Sommer & Lipman[c] |
| Molybdenum | 1939 | Arnon & Stout[c] |
| Chlorine | 1954 | Broyer, Carlton, Johnson, & Stout[c] |
| Nickel | 1987 | Brown, Welch, & Cary (11) |

[a] The dates and researchers that are listed are those on which published articles amassed enough information to convince other researchers that the elements were plant nutrients. Earlier work preceding the dates and other researchers may have suggested that the elements were nutrients.

[b] Cited by Reed (22).

[c] Cited by Chapman (13).

individuals contributed to the discovery of the essentiality of elements in plant nutrition. Much of the early research focused on the beneficial effects or sometimes on the toxic effects of the elements. Generally, an element was accepted as a plant nutrient after the body of evidence suggested that the element was essential for plant growth and reproduction, leading to the assignment of certain times and individuals to the discovery of its essentiality (Table 1.1).

Techniques of hydroponics (8,9) initiated in the mid-1800s and improved in the 1900s enabled experimenters to grow plants in defined media purged of elements. Elements that are required in considerable quantities (*macronutrients*), generally accumulating to 0.1% and upward of the dry mass in plant tissues, were shown to be nutrients in the mid-1800s. Most of the elements required in small quantities in plants (*micronutrients*), generally accumulating to amounts less than 0.01% of the dry mass of plant tissues, were shown to be essential only after techniques were improved to ensure that the water, reagents, media, atmosphere, and seeds did not contain sufficient amounts of nutrients to meet the needs of the plants. Except for iron, the essentiality of micronutrients was demonstrated in the 1900s.

Beneficial elements may stimulate growth or may be required by only certain plants. Silicon, cobalt, and sodium are notable beneficial elements. Selenium, aluminum, vanadium, and other elements have been suggested to enhance growth of plants (3,10). Some of the beneficial elements may be classified in the future as essential elements as developments in chemical analysis and methods of minimizing contamination during growth show that plants will not complete their life cycles if the concentrations of elements in plant tissues are diminished sufficiently. Nickel is an example of an element that was classified as beneficial but recently has been shown to be essential (11).

Studies of the roles of nutrients in plants have involved several diagnostic criteria that address the accumulation of nutrients and their roles in plants. These criteria include visual diagnosis, plant analysis, biochemical tests, and soil tests.

## 1.2 DIAGNOSTIC CRITERIA

### 1.2.1 Visual Diagnosis

Careful observations of the growth of plants can furnish direct evidence of their nutritional conditions. Metabolic disruptions resulting from nutrient deficiencies provide links between the function of an element and the appearance of a specific visible abnormality. Symptoms of disorders, therefore, provide a guide to identify nutritional deficiencies in plants. Careful experimental work and observations are needed to characterize symptoms. For example, nitrogen is needed for protein synthesis and for chlorophyll synthesis, and symptoms appear as a result of the disruption of these processes. Symptoms of nitrogen deficiency appear as pale-green or yellow leaves starting from the bottom and extending upward or sometimes covering the entire plant. Magnesium deficiency also affects protein synthesis and chlorophyll synthesis, but the symptoms may not resemble those of nitrogen deficiency, which affects the same processes. Experience is necessary to distinguish the symptoms of nitrogen deficiency from symptoms of magnesium deficiency or in the identification of the deficiency of any nutrient.

Symptoms on foliage have been classified into five types (12): (a) chlorosis, which may be uniform or interveinal (Figure 1.1); (b) necrosis, which may be at leaf tips or margins, or be interveinal (Figure 1.2); (c) lack of new growth, which may result in death of terminal or axillary buds and leaves, dieback, or rosetting (Figure 1.3); (d) accumulation of anthocyanin, which results in an overall red color (Figure 1.4); and (e) stunting with normal green color or an off-green or yellow color (Figure 1.5). Symptoms of deficiency can be quite specific according to nutrient, especially if the diagnosis is made early in the development of the symptoms. Symptoms may become similar among deficiencies as the intensities of the symptoms progress.

Generalities of development of deficiency symptoms can be made among species. Many references are available with descriptions, plates, or keys that enable identification of nutrient deficiencies (12–20). As mentioned above, for example, nitrogen deficiency appears across plant species as chlorosis of lower or of all leaves on plants. Advanced stages of nitrogen deficiency can lead to leaf death and leaf drop. Nitrogen-deficient plants generally are stunted and spindly in addition to

**FIGURE 1.1** Interveinal chlorosis of iron-deficient borage (*Borago officinalis* L.). (Photograph by Allen V. Barker.) (For a color presentation of this figure, see the accompanying compact disc.)

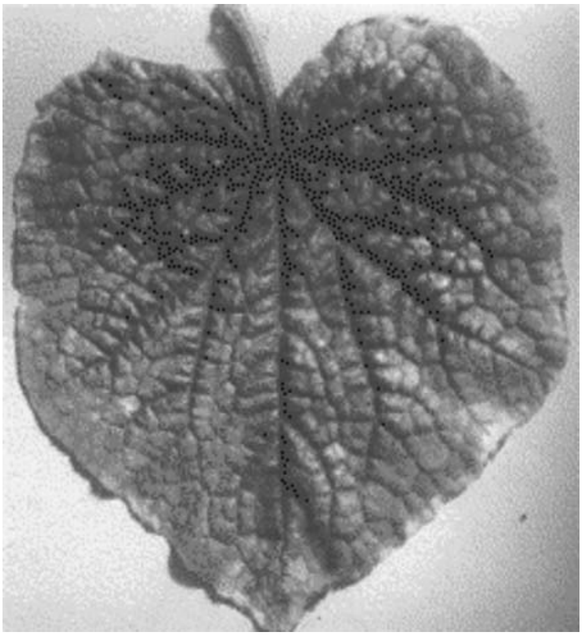

**FIGURE 1.2** Deficiency symptoms showing necrosis of leaf margins, as in this case of potassium deficiency on cucumber (*Cucumis sativus* L.) leaf. (Photograph by Allen V. Barker.) (For a color presentation of this figure, see the accompanying compact disc.)

showing the discoloration that is imparted by chlorosis. Potassium-deficient plants have marginal and tip necrosis of lower leaves. On the other hand, for elements that are immobile (not transported in phloem) or slowly mobile in plants, the deficiency symptoms will appear on the young leaves first. The symptoms might appear as chlorosis, as with sulfur, iron, manganese, zinc, or copper deficiency, or the symptoms might be necrosis of entire plant tips, as occurs with boron or calcium deficiency. Brooms or rosetting may occur in cases where deficiencies (e.g., copper or zinc) have caused death of the terminal bud and lateral buds have grown or where internode elongation has been restricted by

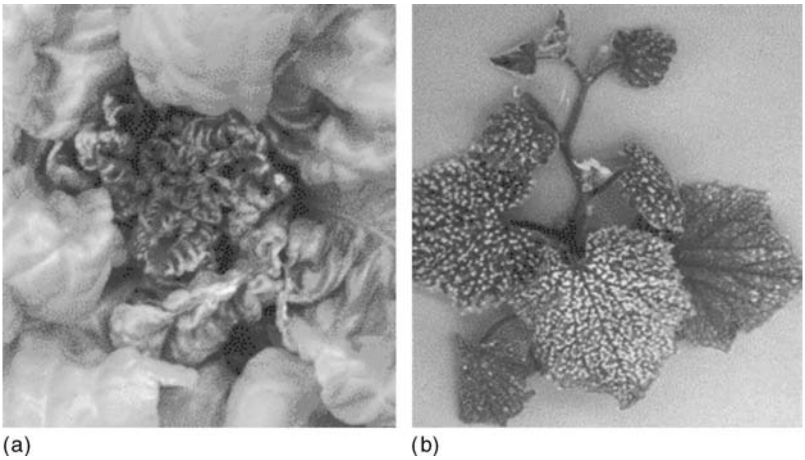

**FIGURE 1.3** Deficiency symptoms showing necrosis on young leaves of (a) calcium-deficient lettuce (*Lactuca sativa* L.) and necrosis on young and old leaves of (b) calcium-deficient cucumber (*Cucumis sativus* L.). With cucumber the necrosis has extended to all leaves that have not expanded to the potential size of full maturity. (Photographs by Allen V. Barker.) (For a color presentation of this figure, see the accompanying compact disc.)

**FIGURE 1.4** Stunting and development of red color and loss of green color of phosphorus-deficient tomato (*Lycopersicon esculentum* Mill.). (Photograph by Allen V. Barker.) (For a color presentation of this figure, see the accompanying compact disc.)

nutrient (e.g., zinc) deficiencies. Accumulation of anthocyanin, exhibited by reddening of leaves, may indicate phosphorus deficiency, although nitrogen deficiency can lead to a similar development. Some people try to distinguish the two deficiencies by noting whether the symptoms of reddening develop between the veins (phosphorus deficiency) or along the veins (nitrogen deficiency). Stunting is a good indication of nutrient deficiency, but often stunting cannot be recognized unless a well-nourished plant is available as a standard of comparison. A stunted plant may have normal color and not be recognized as being deficient until abnormal coloration develops with advanced stages of deficiency. In some cases, symptoms may not develop during the growth cycle of crops, but yields may be suppressed relative to plants that have optimum nutrition. *Hidden hunger* is a term applied to cases where yield suppression occurred but symptoms did not develop.

Deficiency symptoms can occur at any stage of growth of a plant. The most typical symptoms are those that appear early in the cycle of deficiency. Early diagnosis of deficiencies may also allow

**FIGURE 1.5** Cabbage (*Brassica oleracea* var. *capitata* L.) plants showing symptoms of stunting. Left: stunting and dark green color diagnosed as being caused by salinity in nutrient solution. Middle: stunting and mottling of foliage due to condition diagnosed as magnesium deficiency. Right: stunting and discoloration of foliage due to condition diagnosed as phosphorus deficiency. (Photographs by Allen V. Barker.) (For a color presentation of this figure, see the accompanying compact disc.)

time for remedial action to take place. Generally, however, if symptoms have appeared, irreparable damage has occurred, with quantity or quality of yields being suppressed or diminished with annual crops or with slowing or damaging of growth and development of perennial crops. Also, symptoms that resemble nutrient deficiency can develop on plants as a result of conditions that are not related to nutrient deficiencies, for example, drought, wet soils, cold soils, insect or disease infestations, herbicide damage, wind, mechanical damage, salinity, or elemental toxicities. Deficiency symptoms are only one of several diagnostic criteria that can be used to assess the nutritional status of plants. Plant analysis, biological tests, soil analysis, and application of fertilizers containing the nutrient in question are additional tools used in diagnosis of the status of plant nutrition.

### 1.2.2 PLANT ANALYSIS

Plant analysis as a means of understanding plant physiology perhaps started with de Saussure (21). With plant analysis, de Saussure corrected the misunderstanding at the time that the mineral matter of plants had no importance. He showed that the mineral matter in plants came from the soil and not from the air and that little growth of plants occurred if they were grown in distilled water. Through plant analysis, he also demonstrated that plants absorbed minerals in ratios that differed from the proportions existing in solution or in soil and that plants absorbed substances from solution, whether the substances were beneficial to the plants or not.

Plant analysis was one of the means used by scientists in the 1800s to determine the essentiality of chemical elements as plant nutrients (22). Further refinements and applications of plant analysis led to studies of the relationship between crop growth or yield and nutrient concentrations in plants (23–26). Elemental analysis of leaves is commonly used as a basis for crop fertilizer recommendations (27,28).

Plants can be tested for sufficiency of nutrition by analytical tests, which employ quantitative analysis (total or specific components) in laboratories, or by *tissue tests* (semiquantitative analysis), often applied in the field. With proper means of separation of constituents, quantitative tests may measure nutrients that have been incorporated into plant structures or that are present as soluble constituents in the plant sap. The tissue tests generally deal with soluble constituents.

### 1.2.3 QUANTITATIVE ANALYSIS

Quantitative plant analysis has several functions in assessing the nutrient status of plants (29). Among these functions, plant analysis can be used to confirm a visual diagnosis. Plant analysis also can help in identifying hidden hunger or incipient deficiencies. In confirming diagnoses or in identifying incipient deficiencies, comparisons are made between laboratory results and critical values or ranges that assess the nutritional status as deficient, low, sufficient, or high, or in other applicable terms. The *critical concentration* of a nutrient is defined as the concentration of the nutrient below which yields are suppressed (26,30). In the determination of critical concentration, analysis of a specific tissue of a specific organ at a designated state of development is required. Because of the amount of work involved, critical concentrations are rarely determined; consequently, *ranges of sufficiency* are most commonly used in assessment of plant nutrition (27). For each nutrient or beneficial element mentioned in this handbook, ranges of sufficiency are reported.

For any plant, it could be that only one nutrient is deficient or in excess, but it is also possible that more than one nutrient may be out of its range of sufficiency. Furthermore, the actual requirement for an individual nutrient may be different if other nutrients are not present in the plant above their own critical concentrations. For this reason, it is becoming common to consider concentrations of nutrients in relation to the concentrations of other nutrients within the plant. Forms of multivariate analysis such as *principal component analysis* and *canonical discriminant analysis* have been used to investigate relationships between the internal concentrations of many nutrients together and plant growth (31). Currently, a commonly used application of plant analysis is the Diagnosis and Recommendation Integrated System (DRIS), which compares ratios of concentrations of all the possible pairs of elements analyzed to establish values that help to identify nutrients that are most likely to be deficient (32,33).

Plant analysis is also used to determine if an element entered a plant. Fertilization is employed to correct deficiencies, often in response to a visual diagnosis. It is important to know that nutrients actually entered plants after the application of the nutrients to the soil or foliage. No response to the application of a nutrient may be understood as meaning that the element was not lacking, when in fact, it might not have been absorbed by the plant being treated. Plant analysis can also indicate the effects of application of plant nutrients on plant composition with regard to elements other than the one being studied. Interactions may occur to enhance or to suppress the absorption of other nutrients. In some cases, growth may be stimulated by a nutrient to the point that other nutrients become deficient, and further growth cannot occur. Plant analysis can help to detect changes in plant composition or growth that are synergistic or antagonistic with crop fertilization.

Collecting samples of plant organs or tissues is important in assessing nutrition by plant analysis. Comparable leaves or other organs or tissues from the same plant or from similar plants should be collected as samples that show symptoms and samples that do not. Samples of abnormal and normal material from the same plant or similar plants allow for development of standards of comparison for deficient, optimum, or excessive nutrition. The composition of plants varies with time (diurnal and stage of growth) and with parts of plants as well as with nutrition (34). It is wise to take samples from plant parts that have been studied widely and for which published standards of comparisons for deficient, sufficient, and optimum concentrations of nutrients are available. Jones and Steyn (35) discuss methods of sampling and sample preparation prior to analysis, along with methods of extracting nutrients for analysis and methods of analysis of plant tissues. A handbook edited by Kalra (36) also addresses sampling and analysis of plant tissues.

### 1.2.4 TISSUE TESTING

Plant tissue testing is a technique for rapid determination of the nutritional status of a crop and is often conducted on the field sites where crops are grown. The test generally assesses the nutrient status by direct measurements of the unassimilated fraction of the nutrient in question in the plant. For example, determination of nitrate in leaf petioles, midribs, or blades or in roots is often a chosen tissue test for assessment of the nitrogen status of a plant (37–40). Nitrate in these plant parts represents an unassimilated form of nitrogen that is in transit to the leaves and often shows greater variations in response to soil nutrient relations than determinations of total nitrogen in plant parts, although some research indicates that total nitrogen concentration in the whole plant gives the best index of plant nitrogen nutrition (41). Generally, in a tissue test, the sap of the tissues is extracted by processes such as crushing or grinding along with filtering to collect liquid for testing (34). Testing of a component, such as nitrate in the sap, is often done by semiquantitative determinations with nitrate-sensitive test strips (37,40,42,43), by hand-held nitrate-testing meters (44), or by quantitative laboratory measurements (45). In tissue testing, ammonium determinations are used less often than nitrate determinations because accumulation of ammonium can be an artifact of sampling and analysis (46).

An exception to the direct determination of an element to assess deficiency was the corn (*Zea mays* L.) stalk test of Hoffer (47). This test was based on the observation that insoluble iron compounds appeared at the nodes of corn plants under stress of potassium deficiency (48). The corn stalk test provided only a rough indication of the potassium nutrition of the plant but had a fair agreement with other tests for potassium deficiency and had some application to crops other than corn (34). Similarly, Leeper (49) noted that manganese-deficient oats (*Avena sativa* L.) accumulated nitrate in stems.

Selection of the plant part for testing varies with the nutrient being assessed. With nitrate, it may be important that conductive tissue be selected so that the sampling represents the nutrient in transit to a site of assimilation and before metabolic conversions occur. However, potassium is not assimilated into organic combinations in plants; hence, selection of a plant part is of lesser importance than with determination of nitrate, and leaf petioles, midribs, blades, or other tissues can be used for potassium determination by quick tests or by laboratory measurements (50,51).

Color of leaves can be used as a visual assessment of the nutrient status of plants. This assessment can also be quantitative in a quick test, and chlorophyll-measuring meters have been used to nondestructively evaluate the nitrogen status of plants (52). The meters have to be used in reference to predetermined readings for plants receiving adequate nutrition and at selected stages of development, which are usually before flowering and maturation. Correlations of readings with needs for nitrogen fertilization may not be good as the plant matures and flowers and as materials are transported from leaves to fruits.

Leaf canopy reflectance (near-infrared or red), as employed in remote sensing techniques, can be used to assess the nutrient status of fields. Reflectance has been shown to be related to chlorophyll concentrations and to indicate the nitrogen status of crops in a field (53).

### 1.2.5 BIOCHEMICAL TESTS

Activities of specific enzymes can provide rapid and sensitive indicators of nutrient deficiencies in plants (54). Deficiencies of micronutrients can lead to inhibited activities of enzymes for which the nutrient is part of the specific enzyme molecule. Assays of enzymatic activity can help identify deficiencies when visual diagnosis does not distinguish between deficiencies that produce similar symptoms (55), when soil analysis does not determine if nutrients enter plants, or when plant analysis does not reflect the concentration of a nutrient needed for physiological functions (56). The enzymatic assays do not give concentrations of nutrients in plants, but the enzyme activity gives an indication of sufficiency or deficiency of a nutrient. The assay can be run on deficient tissue or on tissue into which the suspected element has been infiltrated to reactivate the enzymatic system. The assays are run on crude extracts or leaf disks to provide quick tests (57).

Peroxidase assays have been used to distinguish iron deficiency from manganese deficiency in citrus (*Citrus* spp. L.) (55,58). Peroxidases are heme-containing enzymes that use hydrogen peroxide as the electron acceptor to catalyze a number of oxidative reactions. In this application, during iron deficiency, peroxidase activity is inhibited, whereas during manganese deficiency peroxidase activity may be increased. Iron is a constituent of peroxidase, but manganese is not. Kaur et al. (59) reported associations of limited catalase and peroxidase activities with iron deficiency in chickpeas (*Cicer arietinum* L.). Leidi et al. (60) evaluated catalase and peroxidase activities as indicators of iron and manganese nutrition for soybeans (*Glycine max* Merr.). Nenova and Stoyanov (61) reported that intense iron deficiency resulted in low activities of peroxidase, catalase, and nitrate reductase in corn (*Zea mays* L.). Ranieri et al. (62) observed a suppression of peroxidase activity in iron-deficient sunflower (*Helianthus annuus* L.). On the other hand, carbonic anhydrase has been employed to identify zinc deficiency in citrus (63), sugarcane (*Saccharum officinarum* L.) (64), black gram (*Vigna mungo* L.) (65), and pecan (*Carya illinoinensis* Koch) (66). Zinc deficiency was associated with a decrease in messenger RNA for carbonic anhydrase along with a decrease in carbonic anhydrase activity in rice (*Oryza sativa* L.) (67). In another assay, alcohol dehydrogenase was twice as high in roots of zinc-sufficient rice as in zinc-deficient rice, and activity of alcohol dehydrogenase in roots was correlated with zinc concentration in leaves (68). Ascorbic acid oxidase assays have been used in the identification of copper deficiency in citrus (69). Molybdenum deficiency has been associated with low levels of nitrate reductase activity in citrus (70). Polle et al. (71) reported that the activities of superoxide dismutase and some other protective enzymes increased in manganese-deficient leaves of Norway spruce (*Picea abies* L.).

Applications of enzymatic assays for the micronutrient status of plants have not been adopted widely in agronomic or horticultural practice, although interest in usage may be increasing as is shown by the number of investigations associating enzymatic activity with plant nutrients. The peroxidase test in the assessment of iron deficiency has perhaps been employed more than other assays (57,72). Macronutrients have numerous functions in plants, and association of specific enzymatic activity with deficiencies of macronutrients is difficult. However, some assays have been developed, such as nitrate reductase activity for assessment of nitrogen deficiency, glutamate-oxaloacetate aminotransferase for phosphorus deficiency, and pyruvic kinase for potassium deficiency (54). Measurement of pyruvic kinase activity may also be useful for establishing the optimum balance between potassium, calcium, and magnesium concentrations in tissues (73).

### 1.2.6 SOIL TESTS

A soil test is a chemical or physical measurement of soil properties based on a sample of soil (74). Commonly, however, a soil test is considered as a rapid chemical analysis or quick test to assess the readily extractable chemical elements of a soil. Interpretations of soil tests provide assessments of the amount of *available nutrients*, which plants may absorb from a soil. Recommendations for fertilization may be based on the results of soil tests. Chemical soil tests may also measure salinity, pH, and presence of elements that may have inhibitory effects on plant growth.

A basic principle of soil testing is that an area can be sampled so that chemical analysis of the samples will assess the nutrient status of the entire sampled area. Methods of sampling may differ with the variability of the area being sampled and with the nutrients being tested. A larger number of samples may need to be taken from a nonuniform area than from a uniform area. Movement of nutrients into the soil, as with nitrate leaching downward, may cause the need for sampling of soil to be at a greater depth than with nutrients that do not move far from the site of application. Wide differences in test results across a field bring into question whether a single recommendation for fertilization can be made for the entire field (74,75). Fertilization of fields can increase the variability of nutrients of a field, and the assessment of the fertility level with respect to nutrients will become more difficult. Variations in patterns of applications of fertilizers, such as placement of fertilizers in bands in contrast to broadcasting of fertilizers, can affect soil samples. The proceedings of an international conference on precision agriculture addressed variability in fields, variable lime and fertilizer applications in fields, and other factors involved in site-specific collection of data, such as soil samples (76).

Results of soil tests must be calibrated to crop responses in the soil. Crop responses, such as growth and yields, are obtained through experimentation. In the calibrations, the results of soil tests are treated as independent variables affecting crop growth and yields; otherwise, all other variables such as weather, season, diseases, soil types, weeds, and other environmental factors must be known and interpreted. The consideration of results of soil test as independent variables may impart difficulties in interpreting the results, especially if the environmental factors have marked effects on crop yields.

Results of soil analysis, sometimes called *total analysis*, in which soil mineral and organic matter are destroyed with strong mineral acids, heat, or other agents do not correlate well with crop responses (77). Generally, soil tests involve determination of a form of a plant nutrient with which a variation in amount is correlated with crop growth and yield. These forms of nutrients are commonly called *available plant nutrients*. The different forms of nutrients are extracted from the soil with some solvent. Many different methods of extraction of soil samples are being used for measurement of available nutrients in soils. Extractants are various combinations of water, acids, bases, salts, and chelating agents at different strengths. The extractants are designed to extract specific nutrients or are universal extractants (77–83). Much discussion has occurred as to whether one method of extraction is better than another. Morgan (77) noted that any chemical method of soil extraction is empirical and that the results give only an approximate quantitative expression of the various chemical constituents in soil. Morgan stated further that no one solvent acting on the soil for a period of minutes or hours will duplicate the conditions involved in provision of nutrients from soil to plants. Researchers may choose to continue to test soils with extraction procedures with which they have experience and for which they have compilations of results. Researchers who analyze only a relatively few samples may choose to use procedures for which published results are readily and commonly available. Methods of extraction and analysis for specific elements are addressed in several monographs and handbooks (84–86). Chemical analyses are the most accurate part of soil testing since they are chemically reproducible or precise measurements of the amounts of nutrients extracted from soils. Selection of the method of analysis depends largely on the facilities that are available to scientists.

## 1.3 APPROACHES IN RESEARCH

Research in plant nutrition is a continuing program. The development of new crop varieties and the introduction of new management practices to increase crop yields impart changes in nutrient requirements of plants. The increasing application of genomics is providing more understanding of the genetic basis for the efficiency with which different plants utilize nutrients. For example, a study of induction of *Arabidopsis* genes by nitrate confirmed that genes encoding nitrate reductase, the nitrate transporter NRT1 (but not the nitrate transporter NRT2), and glutamate synthase were all highly induced, and this work also demonstrated induction of a further 15 genes that had not previously been shown to be induced (87). Nitrate influences root architecture through induction of genes that control lateral root growth (88).

Research is conducted, and will continue to be conducted, to ensure that soil tests correlate with use of nutrients by plants and that fertilizer recommendations are calibrated for crops (89). These correlations must be developed for individual crops and different land areas. Some research is directed toward development of systems for evaluation of soil and crop conditions through methods other than traditional soil and plant analysis. Much of the past and current research addresses chemical, physical, and biological properties of soils (90,91). Some researchers have studied the interaction of these quantitative aspects to determine *soil quality* and to develop a *soil quality index* that correlates with crop productivity and environmental and health goals (92). Soil quality has been defined to include productivity, sustainability, environmental quality, and effects on human nutrition (93). To quantify soil quality, specific soil indicators are measured and integrated to form a soil quality index.

Research in plant nutrition addresses methods of economically and environmentally sound methods of fertilization. Worldwide, large increases have occurred in the use of fertilizers because of their effects on yields and availability. Traditionally, fertilizer use has followed Sprengel's law of the minimum, made famous by Liebig (94), and the application of the law of diminishing returns by Mitscherlich (95). Applying these two laws has given us fertilizers with the nutrients blended in the correct proportions for the world's major crops and rates of fertilizer use that lead to maximum yields commensurate with the cost of the fertilizer.

More recently, interest has turned to issues related to the impact of this intensified agriculture and fertilizer use on the environment and to greater interest in fertilizer use efficiency to help avoid pollution of land and water resources (96). Research is conducted on dairy manure management to protect water quality from nutrient pollution from the large amounts of nitrogen and phosphorus that may be added to heavily manured land (97,98). In its most extreme manifestation, this interest in avoiding excessive fertilization of farmland has given rise to increased practice of organic farming, where synthetic inorganic fertilizers are eschewed in favor of organic sources of nutrients. Regardless of whether nutrients are supplied from organic or synthetic sources, it is still the same inorganic elements that plants are absorbing.

Research is conducted on the use of plants to clean metal-polluted land. Phytoextraction is a plant-based technology to remove metals from contaminated sites through the use of metal-accumulating plants (99,100). Research interests have focused on identifying plants that will accumulate metals and on methods of enhancing accumulation of metals in plants (101–103). Another suggested use of knowledge about the uptake of mineral elements by plants is in the identification of geographical origin of foodstuffs. Analysis of 18 elements in potato tubers has been shown to give a distinctive signature that allows a sample to be correctly assigned to its place of origin, something that could be of great use in tracing of foodstuffs (104).

Research also gives attention to the accumulation of elements that are beneficial in plant, animal, and human nutrition. Accumulation of selenium is addressed in research and in this handbook (105,106). Chapters on aluminum, cobalt, and silicon discuss research on these elements.

Traditional soil testing provides information on patterns in soil fertility and management, and plant vigor provides an indication of plant response to soil properties and management often based on soil testing. Shortcomings of current soil testing methodology are the inability to predict yields, large soil test spatial and temporal variability, inability to reflect dynamics of field parameters that affect nutrient availability, lack of accurate tests for nutrient mineralization, and lack of accurate nutrient response functions (107).

Precision agriculture considers spatial variability across a field to optimize application of fertilizer and other inputs on a site-specific basis (76,90,108–110). Precision agriculture employs technologies of global positioning and geographic information systems and remote sensing. These technologies permit decisions to be made in the management of crop-yield-limiting biotic and abiotic factors and their interactions on a site-specific basis rather than on a whole-field basis (111–114). Remote sensing is a term applied to research that assesses soil fertility and plant responses through means other than on-the-ground sampling and analysis (115). Research has applied video image analysis in monitoring plant growth to assess soil fertility and management (116). Spectral reflection and digital processing of aerial photographs have been researched to assess soil fertility (117). In precision agriculture, it is possible for the fertilizer spreader on the back of a tractor to operate at different speeds in different parts of a field in response to data obtained on the growth of the crop underneath and stored in a geographic information system. These data may have been obtained by remote sensing, or even by continuous measurement of yields by the harvesting equipment operating in the same field at the previous harvest. The precise location of the fertilizer spreader at any moment of time is monitored by global positioning.

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