MARYLAND COOPERATIVE EXTENSION
UNIVERSITY OF MARYLAND
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Fact Sheet

Fact Sheet 639

Basic Principles of Soil Fertility I: Plant Nutrients

Productive, fertile soils offer basic physical support for plants as well as supplying moisture, air, and nutrients to the roots. Soil fertility and plant nutrition are very important components of the crop production scenario, but the basic principles of soil fertility and plant nutrient management are often taken for granted and sometimes totally ignored by growers. This uninformed perspective ultimately may cost the farmer many extra dollars in suboptimal yields and reduced fertilizer efficiency. Improperly managed nutrients also may create environmental problems if they are allowed to contaminate surface and ground waters.

Crop producers and their advisors need to become more familiar with the essential plant nutrients, their chemical and physical characteristics, their behavior in the soil, and their physiological roles in plant growth.

To more efficiently manage soils, growers must become more familiar with the significance of important soil properties such as texture, structure, organic matter, anion and cation retention, cation exchange capacity (CEC), percent base saturation (BS), and acidity (pH). Just as important, growers must understand the relationship among these characteristics. These topics are discussed in this fact sheet and its companion, "Basic Principles of Soil Fertility II: Soil Properties."

The Essential Plant Nutrients

Sixteen chemical elements have been identified as essential for the growth of most agronomically important plants. Three of these elements–carbon (C), hydrogen (H), and oxygen (O)–are categorized as nonmineral nutrients. Plants obtain them from the atmosphere and from water. These nutrients play an important role in photosynthesis, the process by which plants combine carbon dioxide(CO_2) and water (H_2O) in the presence of light and chlorophyll to form oxygen(O_2) and carbohydrates (CH_2O). Carbon, hydrogen, and oxygen are normally plentiful in the environment and do not need to be added to the soil in the form of fertilizers.

The other 13 chemical elements essential to plant growth are classified as mineral nutrients. They are divided into three basic groups–primary, secondary, and micronutrients. The primary nutrients–nitrogen (N), phosphorus (P), and potassium (K)–frequently are the first to become deficient in the soil because they, especially N and K, are required by plants in the largest quantities. These primary nutrients are the ones most often applied in fertilizers and are represented by the three numbers in a fertilizer analysis, for example, 10-10-10. These digits represent in order, the percent nitrogen (N), phosphorus (P_2O_5),and potassium (K_2O) in a fertilizer grade. Thus, a 100-pound bag of 10-10-10 contains 10 pounds each of N, P_2O_5, and K_2O.

The secondary nutrients–calcium (Ca), magnesium (Mg), and sulfur (S)–are just as important as the primary nutrients, but they are required in smaller quantities. Calcium and magnesium are most frequently added to the soil through the application of liming materials, which are needed on most Maryland soils to neutralize soil acidity. In the past, sulfur was sometimes added unintentionally, as an impurity in other fertilizers. But in recent years, because of more frequent identification of sulfur deficiencies in Maryland soils, sulfur is being increasingly considered as the fourth nutrient in the fertilizer analysis, for example, 10-10-10-4 (percent N-P_2O_5-K_2O-S).

The micronutrients boron (B), manganese (Mn), zinc (Zn), copper (Cu), iron (Fe), molybdenum (Mo), and chlorine (Cl) are required by plants in extremely small quantities. Micronutrients are sometimes referred to as "trace" nutrients. They are normally applied only when micronutrient deficiencies have been positively identified in the plant or when soil tests indicate a need.

Primary Nutrients

Nitrogen. Unlike other essential plant nutrients, nitrogen (N) is not found in significant amounts in the rocks and minerals of the earth's crust. Almost all of the soil's nitrogen supply originates from the earth's atmosphere. The air that we breathe contains about 80 percent nitrogen. Unfortunately, elemental nitrogen is an inert gas that must first be converted to ammonium (NH_4^+) or nitrate (NO_3^-) before it can be used by plants.

Most of the nitrogen found in the soil (97 to 98 percent) is in an organic form that is largely unavailable to plants. The remaining 2 to 3 percent of soil nitrogen is inorganic (mineral), mostly ammonium and nitrate ions. A small amount of organic nitrogen is converted each growing season to the inorganic form through a process known as mineralization. The reverse of mineralization, the process in which inorganic nitrogen is used by plants or soil microorganisms and converted back to the organic form, is known as immobilization. Mineralization increases soil nitrogen availability, whereas immobilization combines nitrogen into organic compounds, which renders it temporarily unavailable for plant use. These processes occur simultaneously in the soil. Both reactions depend on microbial activity; thus soil moisture, temperature, pH, and aeration all have an impact on the amount of soil nitrogen available to plants at any given time.

Because most inorganic nitrogen fertilizers are ultimately converted to the soluble and mobile nitrate form (NO_3^-), nitrogen must be managed very carefully when applied to the soil. Because of its negative charge and its high solubility, nitrogen is not retained by the soil's cation exchange capacity and can be easily lost from the root zone by leaching. The amount of NO_3^- nitrogen removed by leaching is difficult to estimate because this process depends largely on soil moisture, temperature, and the net amount of water moving down through the soil profile following precipitation.

Nitrogen can also be quickly lost from the soil in the gaseous form. When surface applied, nitrogen fertilizers (for example, urea or some of the nitrogen in urea-based solutions, such as 30-percent UAN solution can be converted to ammonia gas (NH_3) and be lost to the atmosphere. When soils remain wetter than normal for periods of time in which anaerobic conditions prevail, nitrate fertilizers are often lost through a process known as denitrification. Under anaerobic conditions, where oxygen is limited, nitrate can be biologically reduced to nitrous oxide (N_2O) or even to elemental nitrogen gas (N_2).

Before atmospheric nitrogen can be used by plants, it must be “fixed” by combining it with hydrogen or oxygen. This process occurs in several different ways. Biological symbiotic nitrogen fixation by legumes is a natural process and perhaps the most widely known method. Several strains of *Rhizobium* bacteria form nodules on the roots of host legume plants. These specialized bacteria fix nitrogen from the atmosphere and make it available to the host legume. The amount of nitrogen fixed varies with the type of legume, soil temperature, moisture, pH, and many other factors. Estimates of the extent of this process range anywhere from just a few pounds to several hundred pounds per acre of nitrogen fixed per year.

Some small amount of nitrogen is also fixed naturally by oxidation. The heat generated by lightning causes nitrogen in the air to react with oxygen and form nitrate. The nitrate thus produced is dissolved in atmospheric moisture and falls to the earth as rain and other forms of precipitation.

Industrial nitrogen fixation is the process by which nitrogen from the atmosphere is chemically combined with hydrogen to synthesize ammonia (NH_3). The hydrogen is normally obtained from natural gas or the gases produced from burning coal. This anhydrous ammonia can either be applied directly to the soil by injection, or it can be used as the main “building block” for other forms of nitrogen fertilizer, such as ammonium nitrate, urea, ammonium sulfate, UAN solutions, and ammonium phosphates.

For obvious economic and environmental reasons, nitrogen applications must be managed very carefully. When nitrogen is supplied from a fertilizer or from waste materials, such as manure or sewage sludge, it should be applied at a rate that does not greatly exceed the expected crop nitrogen requirement. It should be applied as near as possible to the time of plant need to reduce the chance for potential losses and to prevent undue nutrient enrichment of the environment.

Phosphorus. Phosphorus is rarely found in the pure elemental form (P) in nature. It is very reactive chemically; thus, it is almost always found combined with other elements–especially oxygen, as $H_2PO_4^-$ or $HPO_4^=$. These orthophosphate forms of phosphorus react quickly with calcium, iron, manganese, aluminum, and other elements to form insoluble compounds that are only slowly available to plants. Phosphorus must be managed very carefully to maximize plant availability.

Available soil phosphorus is derived from the weathering of a number of different minerals, but primarily from the chemical breakdown of apatite, which is composed largely of calcium phosphate.

Most phosphorus compounds formed in the soil are insoluble and are not readily available to plants. A relatively small quantity of the orthophosphate forms are present and can be taken up by plant roots. The soluble orthophosphates ($HPO_4^=$ and $H_2PO_4^-$) have negative charges and are thus not held directly by the negatively charged soil cation exchange capacity. Phosphorus is retained in the soil primarily because of its relative insolubility in water, because of reactions with iron and aluminum in acid soils and with calcium in alkaline soils. This chemical process, which reduces phosphorus availability to plants, is known as phosphorous fixation.

Because the magnitude of phosphorus fixation reactions is strongly influenced by acidity, soil pH management is an extremely important tool for managing phosphorus. Maximum availability of soil phosphorus occurs when soil pH is between 6.0 and 7.5. But even at ideal soil pH levels, a significant quantity of phosphorus remains bound in most Maryland soils and is unavailable to plants.

Soil phosphorus is only slightly water soluble at best, so very little is lost from the soil in drainage water. It has been estimated that approximately one-third of the phosphorus applied as fertilizer each year is available to plants during the current growing season. The rest is retained tightly by the soil through fixation processes that are not completely understood. Plants normally do not require much more phosphorus than calcium, magnesium, or sulfur, but, because of its relative unavailability in the soil, phosphorus must be applied in comparably large quantities.

Because of the low solubility and lack of mobility of phosphorus in the soil, fertilizers can usually be applied to the soil at any time of year without fear of loss as long as the soil particles themselves are not lost through erosion! Phosphorus soil test levels may build up over the years, after repeated fertilizer and manure additions. This phosphorus eventually becomes available for plant uptake. There is little evidence that over-fertilization with phosphorus reduces crop yields, but it does not make sense economically or environmentally. Fertilization is expensive, and in some cases overapplications may contribute to undesirable phosphorus enrichment of the environment.

Potassium. Potassium (K) is required by plants in about the same quantity as nitrogen, in some cases in larger quantities. There is usually much more nitrogen and potassium in plants than there is phosphorus; although it is an essential nutrient, potassium is not bound organically in the plant as nitrogen and phosphorus are. Potassium is mobile in the growing plant and, upon physiological maturity, can rapidly be lost from the plant through leaching.

Although the rock and mineral parent material of most soils of the Piedmont and Mountain regions of Maryland contain many thousands of pounds per acre of potassium, very little is readily available to plants at any one time. Coastal Plain soils do not normally have as many potassium-containing rocks and minerals, and thus they tend to be more potassium deficient than soils of the Piedmont and Mountain regions.

Soil potassium characteristically exists in three forms: (1) unavailable, (2) slowly available, and (3) readily available. The unavailable form of potassium is incorporated in rocks and minerals and is released very slowly with physical and chemical weathering. Slowly available potassium is trapped or fixed between the layers of clay particles. The availability of this form of potassium depends on shrinking and swelling of clay particles during wetting and drying. Readily available potassium may be in the soil solution or in an exchangeable form on the soil colloid. Potassium is a positively charged cation (K^+) that can be held in an exchangeable form by the soil's cation exchange capacity.

Potassium does not move as much in the soil as nitrogen, but potassium is much more mobile than phosphorus. Potassium's mobility is usually driven by its diffusion through water films that surround the soil particles. Because there is less water in the soil during dry weather, potassium is less available to plants during droughts than when soil moisture is optimal. Plant roots must come into direct contact with potassium to absorb it. Therefore, to minimize the effects of drought, it is essential that adequate soil potassium levels be maintained through soil testing and proper fertilization.

Secondary Nutrients

Calcium (Ca), magnesium (Mg), and sulfur (S) are regarded as secondary plant nutrients because they are not required by plants in quantities as large as the primary nutrients. They are nevertheless required in much larger amounts than the micronutrients.

Calcium. Calcium and magnesium exist in the soil as positively charged cations (Ca^{++} and Mg^{++}). Most Maryland soils contain adequate calcium to support plant growth. It is usually the most abundant of the basic cations; thus, even at an unsuitably low soil pH, there is usually adequate calcium to support plant growth. Calcium deficiencies are rare in Maryland soils.

Magnesium. Magnesium deficiency has been identified on all kinds of soils across the State, especially on some of the coarse-textured Coastal Plain soils. There is usually less magnesium in the soil than calcium because magnesium is more soluble and subject to higher leaching losses. Although there are fertilizer materials available to supply calcium and magnesium, both are often routinely and economically added in liming materials. Magnesium deficiency is frequently associated with low soil pH.

Sulfur. Sulfur deficiency has not been a widespread problem in Maryland, but an increasing number of sulfur-deficient soils have been identified in recent years. Unlike calcium or magnesium, available soil sulfur occurs in the soluble sulfate ($SO_4^{=}$) form, which is subject to leaching. Because of increased crop removal of sulfur as a result of higher yields and less sulfur being applied as impurities in other fertilizers (particularly super phosphate, which contains nearly 12 percent sulfur), sulfur fertilizers must now be deliberately applied to many soils on a regular basis. The soils that are most prone to sulfur deficiency are those low in organic matter, particularly the coarser-textured soils of the Coastal Plain region.

Micronutrients

Although copper (Cu) and iron (Fe) are essential to the growth of plants, the only trace or micronutrients that have been demonstrated to be deficient thus far on some Maryland soils are boron (B), manganese (Mn), and zinc (Zn). Molybdenum (Mo) deficiency is very rare and can be best remedied by adjusting soil pH to the recommended level.

Boron is soluble and is thus subject to leaching losses. It is applied frequently to responsive crops such as alfalfa and corn. Because boron is such a potent element, one that can easily result in plant toxicities, it must be applied in very small quantities and usually is broadcast rather than row applied. Boron deficiency has been identified in most soils across the State.

Manganese and zinc are frequently deficient in Coastal Plain soils. Because soil fixation can quickly render these nutrients unavailable to plants, the preferred method of application is a band beside the row.

Applications of micronutrients should always be based on confirmed observations of deficiency symptoms in the field or on soil test results. It is important that micronutrients be applied only when a need for them has been demonstrated; otherwise, micronutrient toxicities can reduce yields, and in severe cases, even kill the plants. Soil pH is an important management tool when applying micronutrients: with the exception of molybdenum, levels of plant-available forms of these elements decrease in response to liming, especially if soil pH is raised to higher than recommended levels.

Summary

The following soil fertility and plant nutrition principles and guidelines regarding essential plant nutrients should be considered carefully to achieve optimum soil and crop management goals:

1. There are 16 nutrients essential for plant growth, 3 of which are classified as organic (carbon, hydrogen, and oxygen). These three nutrients are obtained mostly from the atmosphere. The other 13 inorganic plant nutrients usually must be applied to the soil in fertilizer, manure, compost, or other amendments.
2. The primary plant nutrients (nitrogen, phosphorus, and potassium) are required by plants in relatively large quantities. They are represented by the three numbers of the fertilizer analysis or grade of specific fertilizer, for example, 10-10-10 (which means percent N-P_2O_5-K_2O).
3. The secondary plant nutrients (calcium, magnesium, and sulfur) are required by plants in smaller amounts than the primary nutrients. Calcium and magnesium are often supplied in liming materials. Sulfur is frequently represented as the fourth number of a fertilizer analysis, for example, 10-10-10-4 (percent N-P_2O_5-K_2O-S).
4. Trace or micronutrients (copper, manganese, zinc, boron, iron, molybdenum, and chlorine) are required in extremely small quantities. Care must be exercised in their use to avoid toxicities due to overapplication. Generally, micronutrients should not be applied unless the need for them has been demonstrated by deficiency symptoms or soil tests.
5. All plant nutrients must be managed carefully to achieve maximum uptake efficiency and maximum economic and growth response by the crop, and to cause minimum environmental impact. Proper nutrient management is especially necessary for nitrogen and phosphorus.

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