2

Nutrient Management Module No. 2

CCA
1.5 NM
CEU

Plant Nutrition and Soil Fertility

by Clain Jones and Jeff Jacobsen

Introduction

This module is the second in a series of Extension materials designed to provide pertinent information on a variety of nutrient management, water management, and water quality issues to Extension agents, Certified Crop Advisers (CCAs), consultants, and producers. We have included 15 questions at the back of this module that will make the learning "active" as well as offer the potential for credits for CCAs in Nutrient Management (within the "Plant Nutrition" and "Soil Fertility" competency areas.) In addition, we have included a resource section of other Extension materials, books, web sites, and professionals in the field.

Objectives

After reading this module, the reader should:

1. Know the 17 elements essential for plant nutrition
2. Know the macronutrients and micronutrients
3. Be familiar with the function and mobility of nutrients within plants
4. Understand the forms of each nutrient that are taken up by plants
5. Be familiar with typical nutrient plant concentrations
6. Be able to specify how nutrient needs change during the growing season
7. Understand the basics of nutrient uptake
8. Know the basics of how nutrients are held or released by the soil

Nutrient Management

a self-study course from the MSU Extension Service Continuing Education Series

Montana State University
Extension Service

4449-2
June 2005

Background

Research has determined that plants require 17 nutrients, also called 'essential elements' (Marschner, 1995). Each nutrient assists with different plant functions that allow the plant to grow and reproduce. Each plant nutrient is needed in different amounts by the plant, and varies in how mobile it is within the plant. It is useful to know the relative amounts of each nutrient that is needed by a crop in making fertilizer recommendations. In addition, understanding plant functions and mobility within the plant should prove useful in diagnosing nutrient deficiencies. Factors affecting soil fertility are also important in making sound nutrient management decisions, and are discussed in the second section.

Plant Nutrition

ESSENTIAL ELEMENTS

There are over 100 chemical elements, yet scientists have found that only 17 of them are essential for plant growth (Table 1). To be classified as essential, the element needs to meet the following criteria:

1. The plant cannot complete its life cycle (seed to new seed) without it.
2. The element's function cannot be replaced by another element.
3. The element is directly involved in the plant's growth and reproduction.
4. Most plants need this element to survive.

The fourth criterion is used because some specific plants have been found

Table 1. Essential element, role in plant, and source.

ELEMENT	ROLE IN PLANT	SOURCE
Carbon (C)	Constituent of carbohydrates; necessary for photosynthesis	Air
Hydrogen (H)	Maintains osmotic balance; important in numerous biochemical reactions; constituent of carbohydrates	Water
Oxygen (O)	Constituent of carbohydrates, necessary for respiration	Air/Water
Nitrogen (N)	Constituent of proteins, chlorophyll and nucleic acids	Air/Soil
Phosphorus (P)	Constituent of many proteins, coenzymes, nucleic acids and metabolic substrates; important in energy transfer	Soil
Potassium (K)	Involved with photosynthesis, carbohydrate translocation, protein synthesis, etc.	Soil
Calcium (Ca)	A component of cell walls; plays a role in the structure and permeability of membranes	Soil
Magnesium (Mg)	Enzyme activator, component of chlorophyll	Soil
Sulfur (S)	Important component of plant proteins	Soil
Boron (B)	Believed to be important in sugar translocation and carbohydrate metabolism	Soil
Chlorine (Cl)	Involved with oxygen production in photosynthesis	Soil
Copper (Cu)	A catalyst for respiration; a component of various enzymes	Soil
Iron (Fe)	Involved with chlorophyll synthesis and in enzymes for electron transfer	Soil
Manganese (Mn)	Controls several oxidation-reduction systems and photosynthesis	Soil
Molybdenum (Mo)	Involved with nitrogen fixation and transforming nitrate to ammonium	Soil
Nickel (Ni)	Necessary for proper functioning of the enzyme, urease, and found to be necessary in seed germination	Soil
Zinc (Zn)	Involved with enzyme systems that regulate various metabolic activities	Soil

Source: Colorado State Univ. (www.colostate.edu/Depts/CoopExt/TRA/PLANTS/nutrient.html)

to need certain elements. For example, some crops will respond to silica (Si) when grown on highly weathered soils. In addition, cobalt (Co) is required by bacteria responsible for nitrogen fixation in legumes; therefore, some consider Co to be essential, while others classify it as 'beneficial'. Other beneficial elements include sodium (Na) and vanadium (V). Essentiality is generally determined by growing plants in nutrient solutions with or without a specific element, and observing differences in plant growth or function. Bear in mind that the determination of essentiality is problematic for elements that may be required in only trace amounts, due to the difficulty in keeping all of a certain trace element out of the seed-nutrient solution, especially when plant seeds have substantial amounts of many elements. Due to this fact, it is possible that other elements essential for growth will be discovered at some point.

A limited supply of one of the essential nutrients can limit crop yield, although other factors such as heat or water can also limit yield. The concept that one factor will generally limit yield, or the 'law of the minimum', is illustrated in Figure 1, where the height of water in the barrel represents crop yield. Essentially, the figure shows that nitrogen is initially the factor that limits yield (a), but after N is added, potassium levels control yield (b).

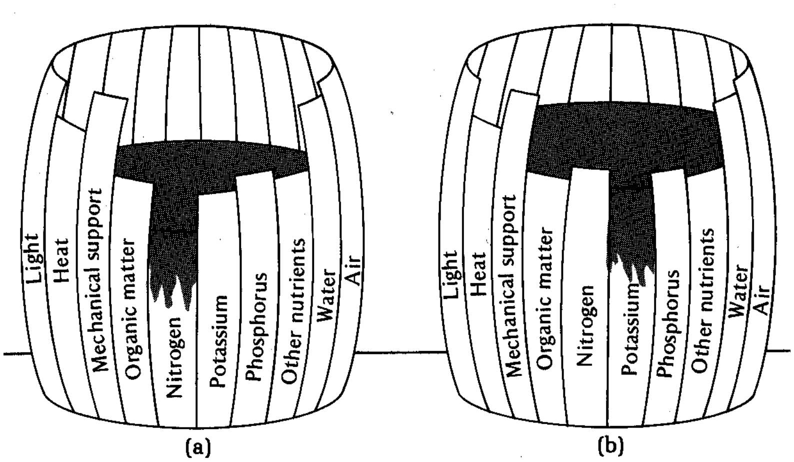

Figure 1. The law of the minimum. From Brady (1984)

Non-mineral Nutrients

Three elements, carbon (C), hydrogen (H), and oxygen (O), are considered to be non-mineral nutrients because they are derived from air and water, rather than from soil minerals. Although they represent approximately 95% of plant biomass, they are generally given little attention in plant nutrition because they are always in sufficient supply.

Table 2. Absorbed nutrient forms and concentrations in dry plant tissue.

Element	Form absorbed	Concentration Range in Dry Plant Tissue
Nitrogen (N)	NO_3^- *(nitrate)* NH_4^+ *(ammonium)*	1 - 5%
Phosphorus (P)	$H_2PO_4^-$, HPO_4^{-2} *(phosphate)*	0.1 - 0.5%
Potassium (K)	K^+	0.5 - 0.8%
Calcium (Ca)	Ca^{+2}	0.2 - 1.0 %
Magnesium (Mg)	Mg^{+2}	0.1 - 0.4%
Sulfur (S)	SO_4^{-2} *(sulfate)*	0.1 - 0.4%
Boron (B)	H_3BO_3 *(boric acid)* $H_2BO_3^-$ *(borate)*	6-60 ppm
Chlorine (Cl)	Cl^- *(chloride)*	0.1-1.0%
Copper (Cu)	Cu^{+2}	5-20 ppm
Iron (Fe)	Fe^{+2} *(ferrous)* Fe^{+3} *(ferric)*	50-250 ppm
Manganese (Mn)	Mn^{+2}	20-200 ppm
Molybdenum (Mo)	MoO_4^{-2} *(molybdate)*	0.05 - 0.2 ppm
Nickel (Ni)	Ni^{+2}	0.1-1 ppm
Zinc (Zn)	Zn^{+2}	25-150 ppm

Q&A #1

Most producers generally apply only N, P, and K. Why is it important for me to learn about the other 11 mineral nutrients?

As Table 2 shows, all of the 14 mineral nutrients are taken up by the crop and then removed from the field at harvest. If these nutrients are not replaced by either commercial fertilizers or organic materials such as manure, the amount of each in the soil will decrease, potentially limiting crop yield. In Montana and Wyoming, there are known cases of B, Cl, Cu, Fe, Mn, and S deficiencies. By knowing the nutrients that could possibly affect yield, you can better diagnose and remedy crop nutrient deficiencies.

MINERAL NUTRIENTS

The 14 mineral nutrients are classified as either macronutrients or micronutrients based on their plant requirements. There are six macronutrients: Nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S). The macronutrients, N, P, and K, are often classified as 'primary' macronutrients, because deficiencies of N, P, and K are more common than the 'secondary' macronutrients, Ca, Mg, and S. The micronutrients include boron (B), chlorine (Cl), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni) and zinc (Zn). Most of the macronutrients represent 0.1 - 5%, or 100-5000 parts per million (ppm), of dry plant tissue, whereas the micronutrients generally comprise less than 0.025%, or 250 ppm, of dry plant tissue (Table 2, previous page). Note that Cl, a micronutrient, has plant tissue concentrations similar to some of the macronutrients. Keep in mind that the classifications of micro vs. macronutrient refer to plant needs rather than plant uptake amounts.

Each nutrient cannot be taken up by plants in its elemental, or non-charged form, but instead is taken up in an 'ionic', or charged, form (Table with the exception of boric acid which is uncharged. Most fertilizers are made up of a combinations of these available nutrient forms, so when the fertilizer dissolves, the nutrients can be immediately available for uptake. Knowing what form of a nutrient the plant absorbs helps us to better focus on what controls the movement of that nutrient in soil.

Plant Uptake of Nutrients

Nutrient uptake by roots is dependent on both the ability of the roots to absorb nutrients and the nutrient concentration at the surface of the root.

ROOTS

Roots are composed of both a mature zone near the shoot, and an 'elongation zone' near the root tip, or cap (Figure 2). Nutrients and water move freely through this elongation zone into the center of the root (the xylem), and then up into the shoot. It is more difficult for nutrients to enter the root through the more mature zone of the root due to a restriction called a 'Casparian strip'. Therefore, nutrient levels in deep soil likely become more important later in the growing season, especially for deep-rooted plants. Roots spread out both laterally and vertically as the plant grows to take advantage of areas within the soil that have more water and nutrients.

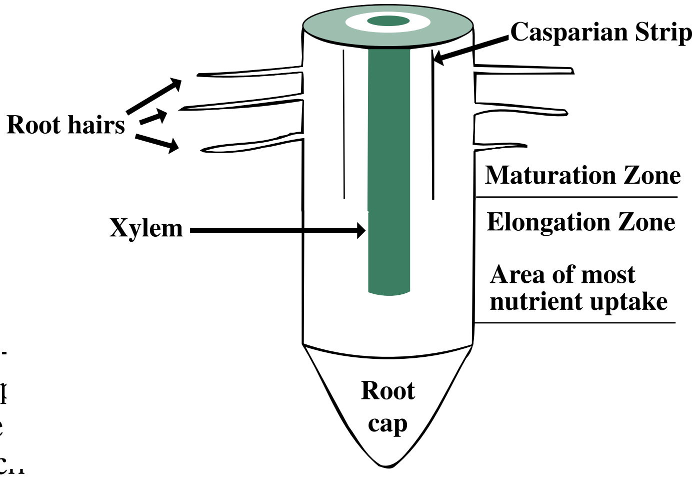

Figure 2. Cross-section of lower portion of root

Nutrient mobility within the plant

All nutrients move relatively easily from the root to the growing portion of the plant through the xylem. Interestingly, some nutrients can also move from older leaves to newer leaves if there is a deficiency of that nutrient. Knowing which nutrients are 'mobile' (i.e., able to move) is very useful in diagnosing plant nutrient deficiencies because if only the lower leaves are affected, then a mobile nutrient is most likely causing the deficiency. Conversely, if only the upper leaves show the deficiency, then the plant is likely deficient in an immobile nutrient, because that nutrient cannot move from older to newer leaves. Table 3 lists the six mobile and eight immobile mineral nutrients. Sulfur is one element that lies between mobile and immobile elements depending on the degree of deficiency.

Timing of Nutrient Uptake

Nutrient uptake does not necessarily match plant growth. For example, when corn biomass represents 50% of its total mature biomass, it has accumulated approximately 100% of its mature K, 70% of its N, and 55% of its P (Figure 3). Therefore, supplying sufficient K and N early in a crop's growing season is likely more important than during the middle of the growing season. However, late in the growing season, nutrients accumulate in the grain rather than in the leaves or stalk. Therefore, late season nutrient application may increase both quality and grain yield if other plant requirements are met, such as water. For example, nitrogen topdressed at tillering has been found to increase both yield and protein of winter wheat grown in Montana, especially at low soil N levels (Lorbeer et al., 2000). Therefore, it is important to understand nutrient needs and timing of nutrient uptake for each crop that you're working with. See the References, Books, and Web Resources at the end of this module for some resources on some specific crops.

Table 3. Mobile and immobile nutrients in plants.

Mobile Nutrients	Immobile Nutrients
Chloride	Boron
Magnesium	Calcium
Molybdenum	Copper
Nitrogen	Iron
Phosphorus	Manganese
Potassium	Nickel
	Sulfur
	Zinc

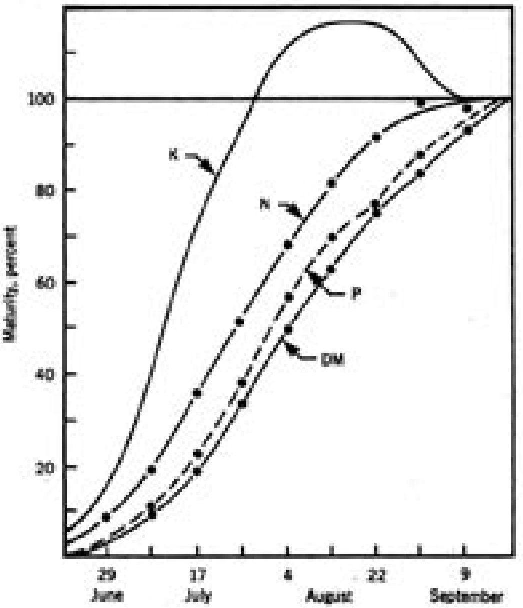

Figure 3. Accumulation of potassium (K), nitrogen (N), phosphorus (P), and dry matter (DM) in corn. (From Foth and Ellis 1997).

Soil Fertility

In the previous chapter, it was pointed out that nutrient uptake is dependent on both the plant's ability to absorb a nutrient and the nutrient level at the root surface. Most soils have far more nutrients than are needed by a plant in a growing season, yet often very little of these nutrients are in solution. This section describes the factors that affect nutrient concentrations in the soil solution and explain the process of how nutrients in the soil solution move toward the root.

TEXTURE

Soil texture, or the relative amounts of sand, silt, and clay, plays a very important role in plant nutrition due to its effect on the ability to retain both water and nutrients. Soils are classified into textural classes by their percentages of sand, silt, and clay (Figure 4). Note that a soil with 20% clay and 45% sand would be classified as a loam. Sand particles are smaller than 2 millimeters (the thickness of a nickel) and larger than 0.05 mm (1/2 the thickness of a piece of paper), and have very little ability to hold water or nutrients due to large pore spaces between particles and low surface area. Conversely, clay particles are smaller than 0.002 millimeters (invisible to the naked eye), and can hold large quantities of water and nutrients. Soils dominated by clay have small pores that prevent water from draining freely and have very high surface areas, ranging up to 90 acres per pound of soil. This high surface area gives nutrients numerous binding places, which is part of the reason that fine textured soils have such high abilities to retain nutrients. The second reason is that clays are often made up of minerals that have net charges on their surfaces (Q&A #2).

Q&A #2

What causes clays to have negative charges?

The negative charge on layer silicates is due to two different processes. Much of the negative charge originates when some cations such as Mg^{+2} replace other cations such as Al^{+3} within the layer silicate structure. This substitution of a smaller charged ion for a larger charged ion during formation of the mineral leaves a net negative charge on the soil particle. The second source of the negative charge originates when a layer silicate particle breaks, exposing 'edge sites' that are mostly negatively charged.

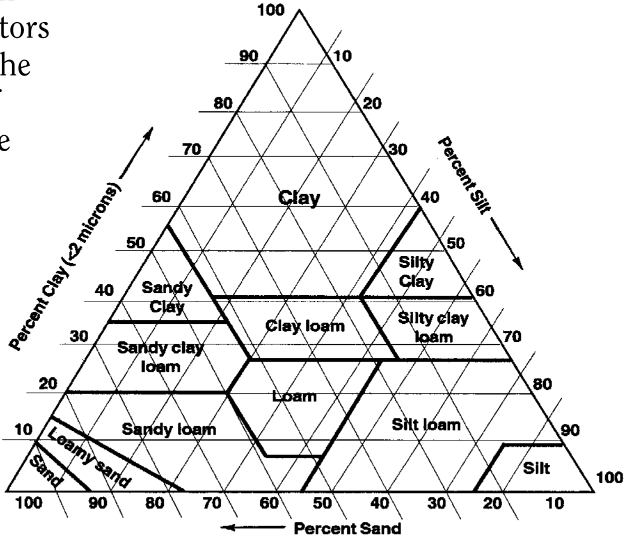

Figure 4. Textural triangle showing the range in sand, silt, and clay for each soil textural class.

CATION AND ANION EXCHANGE CAPACITY

Some soil particles called 'aluminosilicates', or 'layer silicates', have a negative charge that attracts positively charged ions (cations) such as ammonium (NH_4^+) in the same way that hair is attracted to a balloon. Other soil particles, such as iron hydroxides (e.g. rust), have positive charges that attract negatively charged ions (anions), such as sulfate (SO_4^{-2}). Soils generally have much higher amounts of the layer silicates than metal hydroxides; therefore, soils generally have a 'net,' or bottom line, negative charge.

The total negative charge on soil is called the 'cation exchange capacity', or CEC, and is a good measure of the ability of a soil to retain and supply nutrients to a crop. Some typical values of CEC for various soil textures are shown in Table 4.

Note CEC is typically expressed in terms of milliequivalents (or meq) of negative charge/100 g of soil. A meq is equal to 6 $x10^{20}$ charges; therefore, a soil with a CEC of 1 meq/100 g means that there are $6x10^{20}$ negative charges on 100 g (0.22 lb.) of soil. This is a very large number, but because atoms weigh so little, this 0.22 lb of soil would only be able to hold 0.023 grams or 0.0008 ounces of sodium ions (2% of the weight of a standard paper clip). A CEC above about 15 meq/100 g has a relatively high capacity to hold nutrient cations, which include Ca^{+2}, Mg^{+2}, K^{+}, NH_4^{+}, Cu^{+2}, Fe^{+2}, Mn^{+2}, and Ni^{+2}. Soils that are high in clay generally have higher CEC values, although the type of clay can substantially affect CEC. Nutrients that are held by charges on a soil are termed 'exchangeable'. Soil testing (NM Module 1) is often done for exchangeable nutrients, such as K, because it has been found that exchangeable nutrients are available to plants (Q&A #3).

Soils also have the ability to hold anions. This ability is termed the 'anion exchange capacity', or AEC. The AEC is generally smaller than the CEC, but is high enough in most soils to hold substantial amounts of some nutrient anions such as SO_4^{-2}.

ORGANIC MATTER

Organic matter, like clay, has a high surface area and a high CEC, making it an excellent supplier of nutrients to plants. In addition, as organic matter decomposes, it releases nutrients that are bound in the organic matter's structure, essentially imitating a slow release fertilizer. The CEC of organic matter can be as high as 215 meq/100 g, a much higher value than for clay. However, the CEC of organic matter drops substantially as pH decreases as explained in the following section. Organic matter can also hold large amounts of water, which helps nutrients move from soil to plant roots.

pH

The pH of a soil is a measure of the soil's acidity, or hydrogen (H^{+}) concentration. By

Q&A #3

How does CEC affect nutrient availability?

Soils with high CECs hold more positively charged nutrients such as Ca^{+2}. One might think that if the soil is holding, or binding the nutrients, that they are not available to plants. However, these attractions are weak, allowing an exchange between nutrients in the soil solution and nutrients on the soil surface, so as nutrients are removed from solution by a plant, more leave the soil surface and enter solution. Generally, there are many more nutrients attached to the soil than are in solution, so that exchangeable nutrients are a much better measure of available nutrients than solely nutrient concentrations in solution.

Table 4. Cation Exchange Capacities (CEC) for a range of soil textures (FROM BRADY, 1984).

SOIL TEXTURE	CEC RANGE (meq/100g soil)
Sand	2-4
Sandy loam	2-17
Loam	8-16
Silt loam	9-26
Clay	5-58

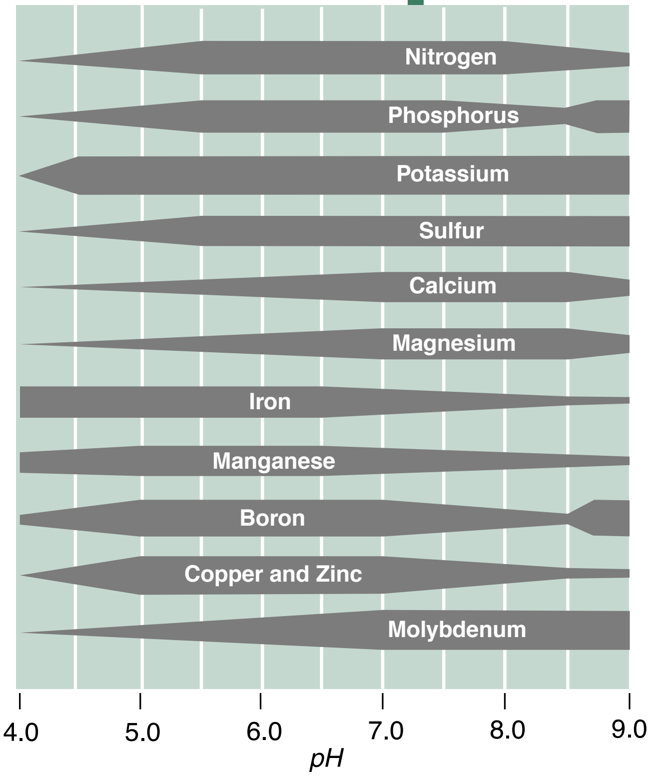

Figure 5. The effect of soil pH on nutrient availability. Thicker bars indicate higher nutrient availability.

(From Hoeft et al., 2000).

definition, pH = -log[H^+], where [H^+] = the hydrogen ion concentration. Because of the negative sign in the definition for pH, acidic soils have low pH values and alkaline soils have high pH levels. Soil pH affects the availability of all of the nutrients (Figure 5). For example, copper, iron, manganese, nickel, and zinc are all more available at low pH levels than at high pH levels because metals are bound very tightly to the soil or exist in solid minerals at high pH. Conversely, the 'base' cations (Na^+, K^+, Ca^{+2}, Mg^{+2}) are bound more weakly to the soil, so can leach out of the surface soil, especially at low pH. Therefore, they are less available at low pH. In Montana and Wyoming, there are many soils with pH levels above 7.5; therefore, there is a higher likelihood for iron, manganese, nickel, copper, zinc, and phosphorus deficiencies than in states with lower pH values, although deficiencies of the micronutrients are not often observed.

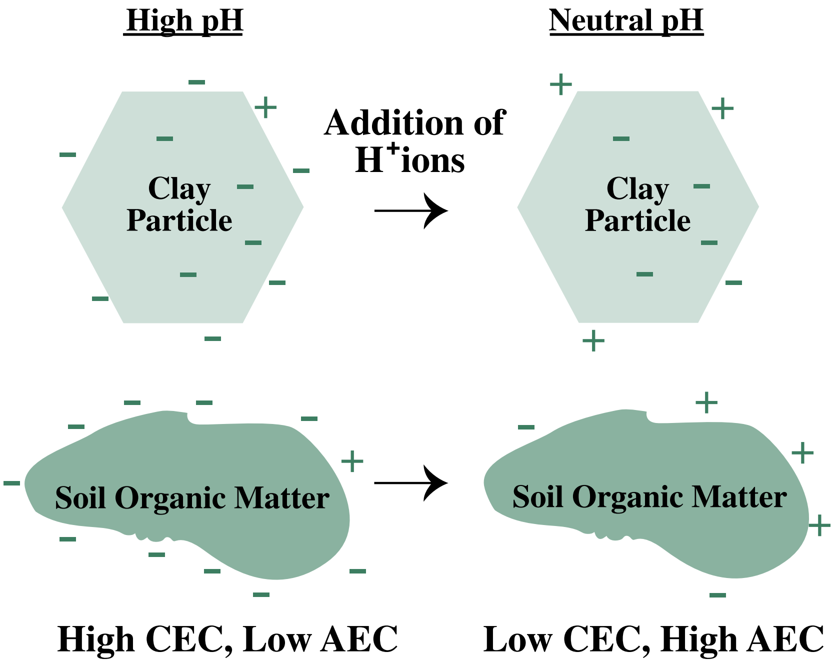

Figure 6. Effect of pH on CEC and AEC of clay particles and soil organic matter. Note decreased pH causes CEC to decrease and AEC to increase (more positive charges).

The optimum pH appears to be near pH 7, but keep in mind that every crop has different nutrient needs, and hence optimum pH levels. For example, sweet clover has been found to have maximum yields near pH 7.5, whereas soybeans and corn grow best near pH 6.8 (Foth and Ellis, 1997).

Lower pH generally causes lower CEC, because the higher concentration of H^+ ions in solution will neutralize the negative charges on clays and organic matter. Fertilizing with ammonia-based fertilizers is one way that pH may decrease over time. Figure 6 demonstrates how pH affects the surface charge, and hence the CEC and AEC of both clay particles and organic matter. The effect of pH on CEC is more pronounced for soil organic matter than for layer silicates, because all of the CEC on organic matter is dependent on pH. Note that the negative charges on the clay particle that are not on the edge of the particle are not neutralized.

NUTRIENT MOBILITY IN SOIL

The previous section discussed the mobility of each nutrient within the plant. The list of mobile and immobile nutrients is somewhat different in soil than in the plant, yet is very important in understanding why some nutrients limit growth more than others. Specifically, nutrient mobility affects how we fertilize. For example, N fertilizer can be broadcast or incorporated with fairly similar results because it is quite mobile. However, P fertilizer is generally either banded or applied with the seed because it is quite immobile in most soils. Table 5 illustrates the relative mobility of each of the 14 essential mineral nutrients. The form of each nutrient is very important in predicting its mobility; therefore, the actual ions are shown rather than just the general nutrient. For example, plants can take up N as either nitrate (NO_3^-) or ammonium (NH_4^+), but NO_3^- moves freely through the soil due partly to its negative charge, whereas NH_4^+ is held by cation exchange sites and, therefore, is less mobile. Keep in mind that this is a generalized table, and the actual relative mobility of each nutrient will depend on pH, temperature, moisture and soil makeup, including the amount of organic matter, layer silicates, and metal hydroxides. For example, some of the immobile nutrients are more mobile than others.

As a good general rule, NH_4^+, K^+, Ca^{+2}, and Mg^{+2} are more mobile than the metals (Cu^{+2}, Fe^{+2}, Fe^{+3}, Mn^{+2}, Ni^{+2}, Zn^{+2}). Fertilizing with any of the mobile elements generally needs to be done more frequently than the immobile elements because the mobile elements are readily taken up or leached compared to the immobile elements. With the exception of NH_4^+, which is quickly converted to NO_3^-, the immobile nutrients can be 'banked', meaning more can be applied than meet crop needs as a way of storing them for the next cropping cycle. 'Soil banking' is also referred to as a 'build' program (see NM Module 1).

Table 5. Mobility of nutrients in soil.

MOBILE	RELATIVELY IMMOBILE
$H_3BO_3^o$, $H_2BO_3^-$	NH_4^+
Cl^-	Ca^{+2}
NO_3^-	Cu^{+2}
SO_4^{-2}	Fe^{+2}, Fe^{+3}
	Mg^{+2}
	Mn^{+2}
	MoO_4^{-2}
	Ni^{+2}
	$H_2PO_4^-$, HPO_4^{-2}
	K^+
	Zn^{+2}

NUTRIENT MOVEMENT TO PLANT ROOTS

Roots come directly in contact with some nutrients (called 'root interception') as they grow; however, this only accounts for approximately 1-2.5% of the total N, P, and K uptake of a plant (Foth and Ellis, 1997). Therefore, other mechanisms must cause the movement of nutrients to the plant.

Water moves toward and into the root as the plant uses water, or transpires. This process, called 'mass flow', accounts for a substantial amount of nutrient movement toward the plant root, especially for the mobile nutrients such as NO_3^-. Specifically, mass flow has been found to account for about 80% of N movement into the root system of a plant, yet only 5% of the more immobile P (Foth and Ellis, 1997). This implies that P (and the other less mobile nutrients) are somehow moving much more quickly than the surrounding water is moving towards the plant roots. It has been found that 'diffusion' accounts for the remainder of the nutrient movement.

Diffusion is the process where chemicals move from an area of high concentration to an area of low concentration. For example, if you open a bottle of ammonia in a closed room, you can soon smell it at the other side of the room because it has diffused from the mouth of the bottle that had high ammonia concentrations, to the areas of the room that previously had no ammonia, or very low concentrations. This same process occurs in soil water, although

Q&A #4

How do the relatively immobile nutrients ever make it to the plant roots?

The plants create a zone directly next to the root that has very low concentrations of these immobile nutrients. This allows diffusion to occur which pulls nutrients that are further away from the root towards the root (described more below). This, in turn, pulls more of these immobile nutrients off the soil surface to maintain a balance between nutrients in solution and nutrients on the surface of the soil.

it generally occurs much slower. By fertilizing near the plant root, the plant is less dependent on exchange processes and diffusion to uptake nutrients, especially P. The nutrients that are most dependent on diffusion to move them toward a plant root are relatively immobile (Table 5), have relatively low solution concentrations, and yet are needed in large amounts by the plant, such as P and K. The secondary macronutrients (Ca, Mg, S) often do not depend on diffusion because their solution concentrations are fairly high in soil relative to plant requirements.

Summary

Plants need 17 elements, called nutrients, to grow and complete their life cycle. Three of these nutrients come from air or water, whereas the other 14 are derived from the soil. Each of the nutrients performs a specific function or functions within the plant, and the amount of each needed by the plant depends largely on function. A limitation of one nutrient can prevent the uptake of others, and ultimately, impact crop yield and quality. Plant uptake of nutrients is dependent on both the ability of the root system to absorb nutrients and the nutrient concentration in soil solution. Nutrient accumulation within the plant is generally faster than biomass accumulation, which is one reason that fertilizing early in the growing season is advantageous.

Soils have large quantities of most nutrients, yet the majority of these nutrients are not in the soil solution, but instead are bound to the soil. Some of these nutrients are available to plants because they are only weakly bound as exchangeable nutrients. The cation exchange capacity (CEC) is one measure of the total amount of exchangeable cations that can be held by the soil, and generally is a good general indicator of soil fertility. CEC is higher in soils with high amounts of clay and organic matter, and is lower in acid soils. Soil pH strongly affects the plant availability of each of the nutrients, with pH levels near 7 generally having optimum availability.

Nutrients vary greatly in their relative mobility within a soil. For example, nitrate (NO_3^-) is highly mobile, yet phosphate (HPO_4^{-2}, $H_2PO_4^-$) is relatively immobile. These differences are key to developing effective nutrient management programs, and explain why applying immobile nutrients such as P near the root system is important for optimum nutrient uptake. Subsequent modules will address each specific nutrient in more detail, with emphasis on factors affecting mobility, uptake, and fertilizer requirements.

References

Brady, N.C. 1984. The Nature and Properties of Soils. 9th Edition. Macmillan Publishing Company. New York. 750 p.

Foth, H.D. and B.G. Ellis. 1997. Soil Fertility. 2nd Ed. CRC Press. Boca Raton, Florida. 290 p.

Hoeft R.G., E.D. Nafziger, R.R. Johnson, and S.R. Aldrich. 2000. Modern Corn and Soybean Production. MCSP Publications. Champaign, IL. 353p.

Lorbeer, S.L. J. Jacobsen, P. Bruckner, D. Wichman, and J. Berg. 2000. Capturing the genetic protein potential in winter wheat. Fertilizer Fact Number 23. July 2000. Montana State University Extension Service and Agricultural Experiment Station.

Marschner, H. 1995. Mineral Nutrition of Higher Plants. 2nd Ed. Academic Press. London. 889 p.

Sparks, D.L. 1995. Environmental Soil Chemistry. Academic Press. San Diego. 267 p.

Resources

BOOKS

Western Fertilizer Handbook. 9th Edition. 2001. Soil Improvement Committee. California Fertilizer Association. Interstate Publishers. 351 p. (http://agbook.com/westernfertilizerhb.asp) $35 including shipping.

Plant Nutrition Manual. J. Benton Jones, Jr. 1998. CRC Press, Boca Raton, Florida. 149 p. Approximately $50.

Soil Fertility. Foth and Ellis. 1997. CRC Press, Boca Raton, Florida. 290 p.

Soil Fertility and Fertilizers: An Introduction to Nutrient Management. Havlin, J.L., S.L. Tisdale, J..C. Beaton and W.L. Nelson. 7th edition, 2005. Pearson Prentice Hall. Upper Saddle River, New Jersey. 515 p. approx. $100.

EXTENSION MATERIALS

Fertilizer Guidelines for Montana Crops (EB161), single copy is free.

Online at: http://www.montana.edu/wwwpb/pubs/eb161.html

Or, obtain the above Extension publication (add $1 for shipping) from:

MSU Extension Publications
P.O. Box 172040
Bozeman, MT 59717-2040

See Web Resources below for online ordering information.

PERSONNEL

Engel, Rick. Associate Professor. Montana State University, Bozeman. (406) 994-5295. engel@montana.edu

Jackson, Grant. Associate Professor. Western Triangle Agricultural Research Center, Conrad. (406) 278-7707. gjackson@montana.edu

Jones, Clain. Extension Soil Fertility Specialist. Montana State University, Bozeman. (406) 994-6076. clainj@montana.edu

Westcott, Mal. Western Agricultural Research Center, Corvallis. Phone: (406) 961-3025. westcott@montana.edu

WEB RESOURCES

http://www.montana.edu/publications

Montana State University Publications ordering information on extension materials including information on Fertilizer Guidelines (EB161).

http://agnotes.org

MSU weekly Agronomy notes by Dr. Jim Bauder on range of issues, including fertilizer management. Currently there are 23 notes on Fertilizer Management, and over 300 Agronomy Notes total answering real life questions from producers, extension agents, and consultants.

http://landresources.montana.edu/FertilizerFacts/

Fertilizer Facts summarizing fertilizer findings and recommendations based on field research conducted in Montana by Montana State University personnel.

http://www.agr.state.nc.us/cyber/kidswrld/plant/nutrient.htm

A nice concise summary of each of the essential elements. Source: North Carolina Department of Agriculture.

http://www.ag.ohio-state.edu/~ohioline/b472/fertile.html

Information on macronutrients and micronutrients. Has plant analysis and soil testing information. Source: Ohio State University.

Acknowledgments

We would like to extend our utmost appreciation to the following volunteer reviewers who provided their time and insight in making this a better document:

Ron Carlstrom, Gallatin County Extension Office, Bozeman, MT

Rick Engel, Dept. of Land Resources and Environmental Sciences, MSU, Bozeman, MT

Jeff Farkell, Centrol Inc., Brady, MT

Neal Fehringer, Western Ag Consulting, Billings, MT

Grant Jackson, Western Triangle Agricultural Research Center, Conrad, MT

Kent Williams, Custer County Extension Office, Miles City, MT

Suzi Taylor, MSU Communications Services, Bozeman. Layout and design.

MONTANA STATE UNIVERSITY EXTENSION SERVICE

The programs of the MSU Extension Service are available to all people regardless of race, creed, color, sex, disability or national origin. Issued in furtherance of cooperative extension work in agriculture and home economics, acts of May 8 and June 30, 1914, in cooperation with the U.S. Department of Agriculture, Douglas Steele, Vice Provost and Director, Extension Service, Montana State University, Bozeman, MT 59717.