Lesson 7: Soil Chemical Properties

Soil chemistry is important to study because of its significant effects on crop yields. Obtaining high productivity while at the same time protecting the soil is what good soil stewardship is all about. The relationships among solids, liquids, and air largely determine the productive capacity of the soil.

The chemistry of the surface layer is subject to rapid change caused by fertilizer additions, plant depletion, and erosion. Soil chemistry involves the relationship between the minerals, the water, and other elements in the soil. In soil chemistry, the clay minerals are important. Most clay minerals are composed of silicon and oxygen, called **silicates**. Some silicates that include aluminum are called **aluminosilicates**. Some common names for silicate clay minerals in Missouri are kaolinite, montmorillonite, illite, and vermiculite (the last two are not as abundant).

One of the important factors in soil fertility is the quantity and proper balance of nutrient elements. To learn what amounts of the different plant nutrients should be present in a soil (i.e., how much fertilizer is needed), the **cation exchange capacity (CEC)** of the soil must be determined. The CEC is the soil's capacity to hold and exchange essential cations. Oxygen, silicon, and aluminum make up about 85 percent of the earth's crust, and to a large extent, determine the CEC.

Cation Exchange Capacity (CEC)

All elements—for example, calcium (Ca), magnesium (Mg), and oxygen (O)—are made up of **atoms**. Atoms make up the smallest portion of an element that can take part in a chemical reaction. An atom or group of atoms that has become electrically charged is called an **ion(s)**. For example, the Ca ion has two positive (+) charges, written Ca^{++}. An O ion has two negative (–) charges, written O^{--}.

Many elements, including those in fertilizers and agricultural lime, have either positive or negative ions. Like charges repel and unlike charges attract (compare to magnets). Most ions have from one to four positive or negative charges. In chemical systems, there is always an equal balance of positive and negative charges. For example, a water molecule has two hydrogen ions with one positive charge each which attract one oxygen ion with two negative charges ($H_2O = H^+ H^+ O^{--}$).

The surfaces of clay minerals possess negative electrical properties that attract and hold positively charged ions of elements such as calcium (Ca^{++}), magnesium (Mg^{++}), potassium (K^+), sodium (Na^+), aluminum (Al^{+++}), and hydrogen (H^+). See Figure 7.1. (It should be noted that Na is not calculated on soil tests in Missouri, even though small amounts exist in the soil.) Other elements are held in a similar manner, but they usually occur in smaller quantities in most soils.

Such elements that form positively charged ions are called **cations**, for example, Ca^{++}, Mg^{++}, K^+, Na^+, Al^{+++}, and H^+. Elements that have negative charges are called **anions**, for example, oxygen (O^{--}) and chlorine (Cl^-). Ca^{++}, Mg^{++}, K^+, and Na^+ are often called **bases** because they tend to make the soil alkaline. Hydrogen (H^+) and aluminum (Al^{+++}) are acid cations. They tend to make the soil acidic. The phenomenon of cations being attracted and held by the soil particle surfaces is called **adsorption**. Terms such as "cations," "acids," and "bases" are used in all soil test results.

The very small soil particles are not ions but have several negative charges per particle. **Micelle** (my-cell) is a term used for a negatively charged solid particle composed of clay or organic matter. The term **colloid** often is used to describe clay particles (such as colloidal clay). Micelles contain many negative charges, and the soil water surrounding the micelles contains many positive charges. See Figure 7.1.

Cation Exchange

Micelles exchange acid H^+ ions for Ca^{++}, Mg^{++}, and K^+ bases because the chemical attraction of the bases is much greater than the attraction of hydrogen H^+ ions. These bases are some of the most important plant nutrients. Plant roots exchange H^+ acid ions for the Ca^{++}, Mg^{++}, and K^+ base ions. The process generally is referred to as **cation exchange**. Collectively, the sites of attraction for cations on the surfaces of soil particles and organic matter (micelles) make up the cation exchange capacity (CEC) of the soil. Most of the sites are located on the surfaces of clay particles.

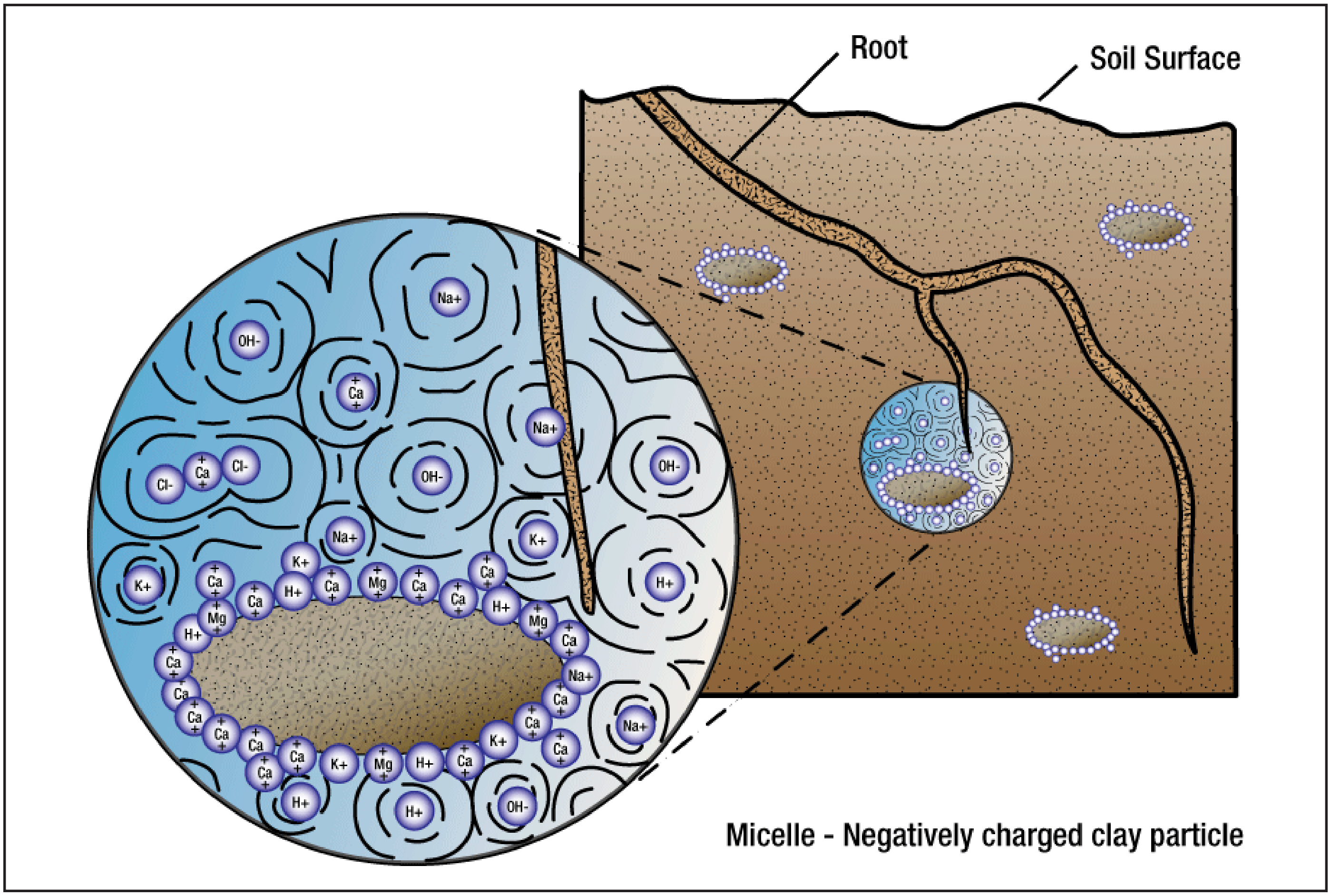
Sites of attraction are always occupied by cations. The cations present in the films of water surrounding the soil particles and in the pores between the particles may exchange places with acid cations adsorbed on the soil particles. Thus, these cations are called **exchangeable cations**. The amount of base cations in relation to the total CEC is referred to as the **percent of base saturation.** Many soil minerals weather to release bases that move either to fill up the exchange capacity or go into soil solution. Either can be used by plants or by microbes. Any excess amounts are leached down through the soil to groundwater and into rivers. Various equilibriums among the plant nutrient elements are established in the soil by cation exchange. This equilibrium affects the ease with which plant roots may obtain the nutrient elements.

High organic matter content contributes greatly to the CEC. Organic matter is used to indicate the amount of N available for crops each year. To learn what amounts of the different exchangeable plant nutrients should be present in a soil, the CEC of the soil must be calculated.

Calculating CEC

How many grams there are of each cation per 100 grams of soil can be determined from the atomic weight of each element and the number of positive charges on each ion. The atomic weight of K = 39, Mg = 24, and Ca = 40. The equivalent weight is calculated by dividing the atomic weight by the number of charges for a particular element. For example, the K ion has only one charge, so 39 (atomic weight) is divided by 1. The weight of Mg or Ca is divided by 2 because each of their ions has two charges. Therefore, the equivalent weight of K = 39 ÷ 1 = 39, Mg = 24 ÷ 2 = 12, and Ca = 40 ÷ 2 = 20. The equivalent weight for an element

Figure 7.1 – Micelle Construction



is equal to the reactive power (attraction) of any other element's equivalent weight. See Table 7.1.

Table 7.1 – Equivalent Weights for Selected Elements

Element	Atomic Weight	No. of Charges	Equivalent Weight
Potassium (K)	39	+1	39
Magnesium (Mg)	24	+2	12
Calcium (Ca)	40	+2	20

Calculations used in determining the cation exchange capacity (CEC) are based on the upper 7 inches of the surface layer (which weighs about 2,000,000 pounds per acre). Each unit of CEC is expressed as milliequivalent (meq) per 100 grams of soil. Although an equivalent of one element is exactly equal in reactive power to an equivalent of any other element, the actual weight of an equivalent will vary among the elements. For each milliequivalent of CEC, the soil will hold any one of the following amounts of the different exchangeable cations as shown in Table 7.2.

Table 7.2 – Milliequivalent Weights of Potassium, Magnesium, and Calcium

Potassium (K)		0.039 g of K / 100 g of soil
	or	0.039 lbs of K / 100 lbs of soil
	or	390 lbs of K / 1,000,000 lbs of soil
	or	780 lbs of K / 2,000,000 lbs of soil
	or	780 lbs of K / acre
Magnesium (Mg)		0.012 g of Mg / 100 g of soil
	or	0.012 lbs of Mg / 100 lbs of soil
	or	120 lbs of Mg / 1,000,000 lbs of soil
	or	240 lbs of Mg / 2,000,000 lbs of soil
	or	240 lbs of Mg / acre
Calcium (Ca)		0.020 g of Ca / 100 g of soil
	or	0.020 lbs of Ca / 100 lbs of soil
	or	200 lbs of Ca / 1,000,000 lbs of soil
	or	400 lbs of Ca / 2,000,000 lbs of soil
	or	400 lbs of Ca / acre

The soil contains various amounts of each of the exchangeable cations. In order to determine the cation exchange capacity of the surface soil, one must obtain the results of a soil test. (A soil test shows what a particular soil sample contains.) The CEC then can be calculated by adding the number of milliequivalents per 100 g of soil occupied by each element. The example in Table 7.4 illustrates this procedure, using information from Table 7.2 and the information from the sample report of a soil test from Table 7.3.

Table 7.3 – Sample Report

Sample Report of a Soil Test

OM %	P_2O_5 lb/A	K lb/A	Mg lb/A	Ca lb/A	NA meq	pHs
2.5	180	390	360	2,400	4.0	5.2

Note: OM = organic matter
NA = neutralizable acidity

It should be noted that only K, Mg, Ca, and neutralizable acids (for example, H and Al) are used to calculate the CEC. The remaining items on the soil test are included here only because they are usually found in an actual soil test report.

Most soil tests will show the individual amounts, in milliequivalents, of Ca, Mg, and K (bases) and H and Al (acids). The total of these is the sum of the cations shown on the soil test. This is the CEC.

The sum of the bases is then divided by the sum of the cations. This figure indicates the percent of the base saturation. For example, the soil test shows the sum of bases = 8 and neutralizable acidity = 4. Therefore, the total cations = 12, 8 ÷ 12 equals 66.6 **percent base saturation.**

Soils are adequately supplied with exchangeable plant nutrients when each unit of the exchange complex contains the proper amounts of K, Mg, and Ca. If the soil has a low exchange capacity, the total amounts of the different nutrients required for good plant nutrition will be lower than if the exchange capacity is high. See Table 7.4.

Table 7.4 – Calculating the CEC

390 lbs/acre of potassium
390 ÷ 780 = **0.5** meq K / 100 g of soil
360 lbs/acre of magnesium
360 ÷ 240 = **1.5** meq Mg / 100 g of soil
2,400 lbs/acre of calcium
2,400 ÷ 400 = **6.0** meq Ca / 100 g of soil
4.0 meq Na / 100 g of soil
Total CEC = **12.0** meq / 100 g of soil

Determining Amount of Fertilizer Needed

Results of field experiments suggest that for each milliequivalent of exchange capacity the soil should contain .02 to .03 meq (approximately 20 lbs) of K per acre, 0.1 meq (24 lbs) of Mg per acre, and 0.75 meq (300 lbs) of Ca per acre. To determine the amount of nutrients needed per acre of a soil with a CEC of 12, simply multiply each of the amounts needed for 1 meq by 12. The following example in Table 7.5 illustrates this procedure.

Table 7.5 – Optimum Nutrient Amounts

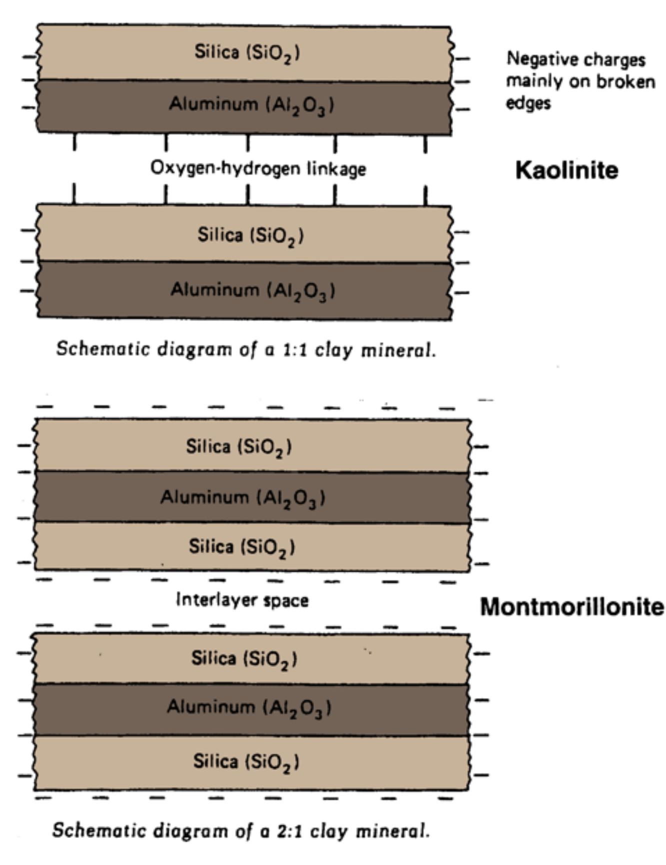
Optimal Amount of Nutrient Per Acre for CEC of 12

K = 20 x 12 = 240 lbs per acre
Mg = 24 x 12 = 288 lbs per acre
Ca = 300 x 12 = 3,600 lbs per acre

Next, compare the results of the soil test (how much K, Mg, and Ca there is) with how much nutrient is needed. For example, the soil test report in Table 7.3 shows that the soil has 390 lbs/A of K. Table 7.5 indicates that the soil should have 240 lbs/A of K. Therefore, no additional K is needed. The soil test report (Table 7.3) indicates that there are 360 lbs/A of Mg, and Table 7.5 indicates that 288 lbs/A are needed. Again, no additional Mg is needed. Lastly, the soil test report indicates that the soil has 2,400 lbs/A of Ca, but Table 7.5 indicates that 3,600 lbs/A are needed. Therefore, additional Ca (1,200 lbs/A) should be added to the soil.

The soil exchange capacity is governed mostly by the amount and kind of clay and the organic matter content in the soil. Therefore, the level of the exchange capacity is related largely to the characteristics of soil texture. Montmorillonite clay has a larger CEC than kaolinite. See Figure 7.2. It should be noted that although phosphorous is not a part of the CEC, field tests indicate that soils which contain more than 120 lbs of phosphorus per acre produced adequate crops.

Figure 7.2 – Schematic Diagram of Kaolinite and Montmorillonite



Soil Properties Affecting the CEC

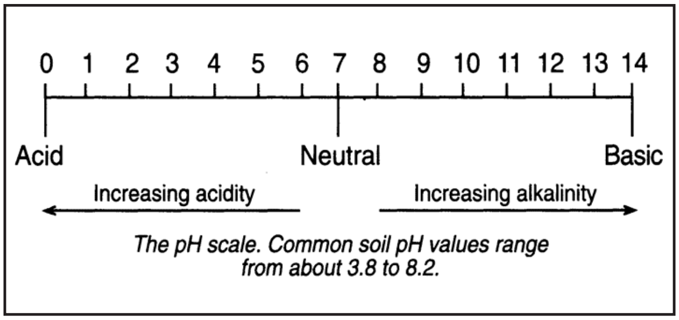
Soils with low clay content, such as sand and sandy loam, have a low CEC, while soils with high clay content, such as silty clay and clay, have a high CEC. Loam and silt loam have a medium CEC. With average organic matter content, loam and silt loam average between 12 and 18 milliequivalents per 100 grams of soil. The effect of textural differences on CEC can easily be seen if soil samples are obtained from uneroded and severely eroded areas of the same field. The sample from the severely eroded area will have much more clay and a much higher CEC. This does not mean that soils should be allowed to erode to get a higher CEC. Eroded soils have higher clay content, but they also have less organic matter, poorer tilth, and lower available water capacity.

Organic matter also has exchange capacity. Soil that contains 4 percent organic matter may have as much as 8 meq per 100 grams of soil. Therefore, the most ideal soil condition is a silt loam with high organic matter content. Also, loam and silt loam have a high available water capacity.

pH

The pH is a scale that measures acidity to alkalinity (0–14). See Figure 7.3. The pH range of Missouri soils is about 4.5–8.4. A few soils may be lower or higher. Neutral pH (or pH 7) occurs when the concentration of H^+ ions and OH^- ions in pure water at 75° F is equal. Neutral pH is neither acid nor alkaline. In 75° water, there are 1.0×10^{-7} g of H^+ ions per liter and an equal number of OH^- ions weighing 17.0×10^{-7} g per liter of water.

Figure 7.3 – The pH Scale



Numbers like 0.0000001N or 1.0×10^{-7} are hard to use. The pH scale simplifies this by changing the –7 exponent to give pH 7. When the concentration of H^+ ions increases, the pH is lower (acid), and when the concentration of OH^- ions increases, the pH is higher (alkaline). It should be noted that the pH increases 10 times between consecutive units. For example, pH 5 is 10 times more acidic than pH 6; pH 6 is 10 times less acidic than pH 5.

Determining pH

Two methods generally are used to determine soil pH. One is water pH (pH_W) and the other is salt pH (pH_S). Salt pH is the more precise method. Water pH is largely a measure of the H^+ ions in the soil solution, while salt pH is a measure of the H^+ ions in the soil solution and the H^+ ions that were attached to soil particles. By adding calcium chloride ($CaCl_2$) to the test solution, the H^+ ions attached to the soil particles are released so they can be measured. The pH_S is a reflection of the **neutralizable acidity (NA)**. The CA^{++} ion in the $CaCl_2$ displaces the H^+ ions on the soil particle. Salt pH generally is about one-half unit lower than water pH.

Importance of pH

The pH value of the soil gives a quick estimate of the balance between the plant nutrient elements in the soil (K, Mg, and Ca) and the other non-nutrient elements, such as H and Al. See Figure 7.4. Strongly acidic soils usually are those that have a relatively low amount of the CEC occupied by K, Mg, and Ca. The pH also indicates if agricultural lime is needed to grow a particular crop. For example, legumes require more neutral soils (pH_W 6.8–7.3) than do such crops such as corn, small grain, and grass (pH_W 6.0–6.8). Some crops (like blueberries) actually require a soil that is quite acid for the best growing conditions. Many trees grow better on soils that are well below a pH_W of 7.

The soil pH alone gives little indication of the amounts of lime needed to correct the nutrient level of a given soil. The lime requirement (Ca) is a function of the CEC. So are the needs for Mg and K. The neutralizable acidity (NA) value is a direct measure of the quantity of acidity that can be neutralized by lime.

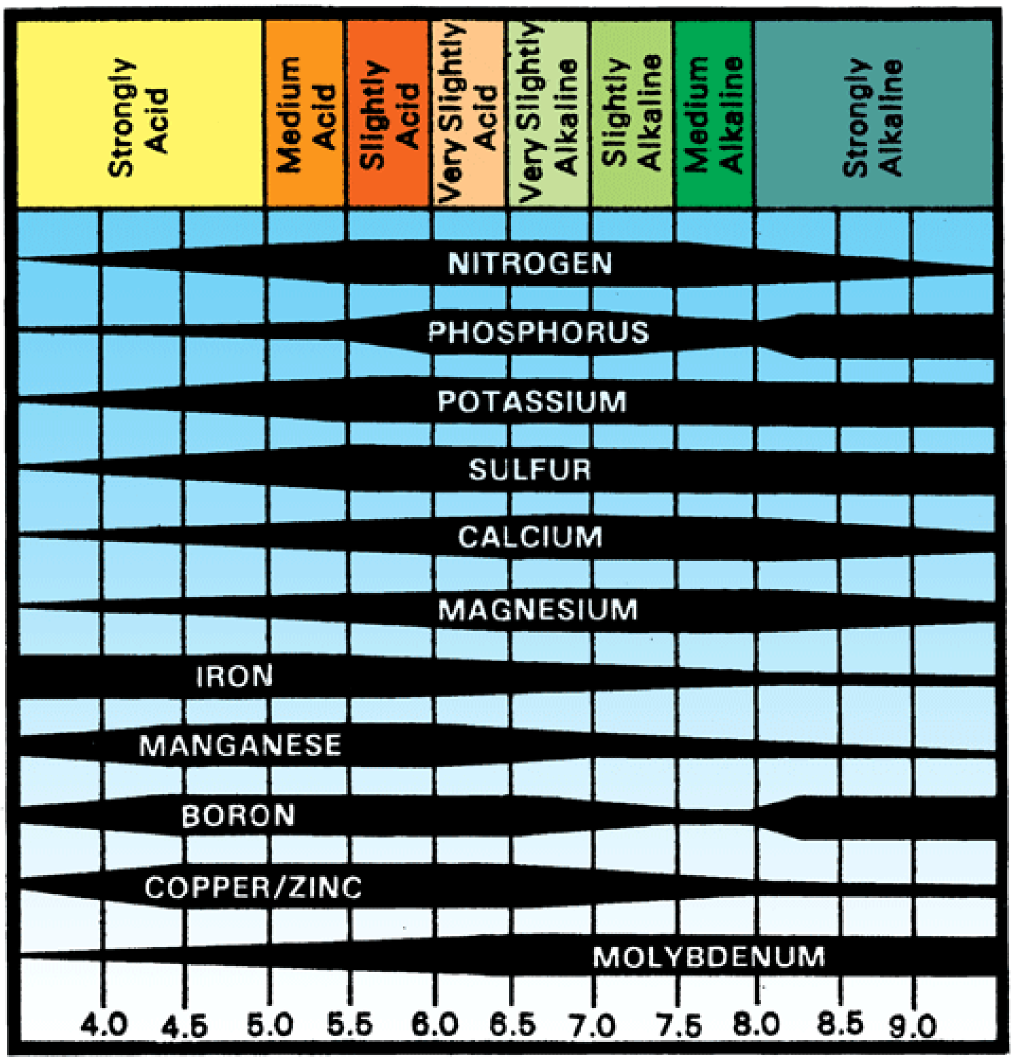
The effect of soil pH_W on pesticides should first be checked by looking for information on the pesticide label, and also by checking with the latest test results from chemical dealers and university experimental data. It is suspected that some herbicides may become overreactive when the soil pH_W is high, causing crops to burn, or there may be dangerous effects with a low soil pH which may cause herbicide carryover into the next crop. High application rates of a coarsely ground agricultural lime may also cause a delayed effect, resulting in an undesirably high pH_w several years after the application.

Correcting Soil pH

Acidity is caused by the leaching (removing) of bases by water or the absorption of base nutrients by growing plants. Growing plants require large amounts of base nutrients. The depletion of Ca can be the greatest cause of increased acidity. By applying lime (calcium carbonate, or $CaCO_3$) the soil pH_s can generally be raised to any desirable level.

Lime does two things for the soil. First, the H^+ on the surface of clay particles (micelles) is replaced by Ca^{++}.

Figure 7.4 – How Soil pH Governs Nutrient Release



Soil pH Governs Nutrient Release

Acidity or alkalinity (pH) controls relative nutrient availability.

Second, the H^+ acts with the CO_3 ion to form carbonic acid (H_2CO_3), which further breaks down to form carbon dioxide gas (CO_2) and water (H_2O). Other materials such as gypsum, which contain Ca, will add Ca^{++} to the soil, but will not raise the pH_S by removing the H^+ in the soil solution.

Crops require different levels of pH for optimal growth. The levels which need to be maintained can only be determined by a soil test. Liming helps to release other non-base plant nutrients and make these nutrients more available to plants. After the nutrients have been used by plants, they have to be replenished by fertilization if a high productive level is to be maintained.

Summary

Soil chemistry and the cation exchange capacity (CEC) are important to study because of their effects on crop yields. Soil chemistry involves the relationship between the minerals, the water, and other soil elements. In soil chemistry, the clay minerals are especially important. CEC is the capacity of the soil to hold and exchange essential nutrients with plants.

The surfaces of clay minerals possess negative electrical properties that attract and hold positively charged ions, called cations. Elements that have negative charges are called anions. Micelles are negatively charged solid particles composed of clay or organic matter. The soil water surrounding the micelles contains mostly positive charges. Micelles exchange H^+ ions (acid cations) for Ca^{++}, Mg^{++}, and K^+ (base cations) because the chemical attraction of the bases is much greater than the attraction of the H^+ acid ions.

The CEC can be calculated using the results of a laboratory soil analysis so that accurate fertilizer recommendations can be made for a particular crop. A method for calculating CEC and the appropriate amount of fertilizer is given in this lesson. The most ideal soil for a high CEC is a silt loam with high organic matter content.

The pH is a scale which measures acidity to alkalinity (0–14). In Missouri, the soil pH range is about 4.5–8.4. There are two kinds of soil tests for pH, water (pH_W) and salt (pH_S). Water pH gives the pH of the acid ions (such as H^+ and Al^{++}) in the soil solution. Salt pH is more precise and gives the total pH of the soil including the acid ions in the soil solution and those attached to the micelles (colloidal particles). Salt pH is generally about one-half unit lower than water pH. Soil pH gives an estimate of the balance between plant nutrient elements (bases) and non-nutrient elements (acids).

The pH_S indicates if agricultural lime is needed for a particular crop, but the exact quantity that is required is a function of the CEC. Each crop has its own level of pH for good production.

Acidity is caused by the leaching of bases by water or the absorption of base nutrients by growing plants. The depletion of calcium can be the greatest cause for increased acidity. The pH can be raised by applying agricultural lime. After nutrients have been used by plants, they need to be replenished by fertilization to maintain a level of high production.

Credits

Brown, J.R., and R.R. Rodriguez. *Soil Testing: A Guide for Conducting Soil Tests in Missouri* (Guide #EC 923). Missouri Cooperative Extension Service, 1983.

Scrivner, C.L., James C. Baker, and Harold E. Grogger. *Evaluating Missouri Soils*. Columbia, MO: University Extension, 1972.

Thompson, L.M., and F.R. Troeh. *Soils and Soil Fertility,* 3rd ed. New York: McGraw-Hill, 1973.