Soil Chemical Composition and Fertility Management
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Wise soil management - throughout history, it has been the foundation of all great civilizations and it is still is the key to our success as farmers. Yet the soil is an amazingly complex system and few people even remotely understand how soil composition affects crop growth, fertility, erosion, and successful tillage. In an effort to improve their comprehension of soil chemical composition as it relates to soil fertility management, the members of the New York Certified Organic, Inc. Chapter assembled a panel of experts for a day long seminar. It must be emphasized that soil chemistry is only one aspect of soil fertility. The role of soil biological and microbial life on soil fertility will be considered more fully at a later time.

Dr. Dick Liebe has recently retired after more than 30 years as a professor in the Geology department at the State University of New York at Brockport. His life long study of sedimentary rocks and the history and forces that composed and changed them has given him a deep appreciation for the complexity of the soils in New York. The land as it appears today is a relatively recent geological development, but it is the cumulative result of many events over a very long time. In order to understand where today's soil comes from, Dr. Liebe started one billion years ago. At that time, the oldest rocks found in the Adirondack Mountains of New York were first forming from massive heat and pressure that resulted from continent collisions. Then followed a long period of erosion and relative geological calm as sea level rose and shallow seas covered much central New York. This period is significant in the soils found today, because the warming and cooling atmosphere created varying conditions at which different chemicals sedimented out of the shallow water and formed rock. When the temperature was high and the atmosphere dry, a calcium-magnesium combination precipitated forming a rock called dolostone. When the temperature was temperate and rainfall near normal, the resulting limestone was high in calcium and low in magnesium. Over millions of years, fluctuating water temperature and water turbulence resulted in layers and zones of sedimentary rock that varied greatly in calcium and magnesium content.

Another continent collision occurred about 350 million years ago, this time uplifting the land that would become the mountains of New England and maritime Canada. These newly revealed rocks were composed of highly stable quartz and the much more erodable feldspar. Feldspar is high in potassium and as the feldspar eroded into tiny particles, potassium rich clay would be formed. Since in different locations, the feldspar was composed of different chemical combinations, the resulting clay varied in potassium, sodium, aluminum, iron, and magnesium content.

Beginning 3 million years ago, the climate grew cold. Huge glacial ice sheets formed, slowly oozing their slow path down over most of the Northern hemisphere. In most places, the glaciers were 1-2 miles thick and moved several inches each year. Anything in the path of the glacier was either picked up or scoured down, effectively changing all surface characteristics. Hill tops were rounded, lake and stream beds deepened, and many rocks were moved far from their point of origin. Gradually the glaciers retreated when the melt rate exceeded the rate of advance. The melt water carried tremendous loads of sand, rock, clay, and other debris. If the retreat was slow and gradual, the deposition of such material was evenly spread over a large area, but if the retreat was rapid, large piles of unevenly sized rocks were dumped to make hills and ridges. This deposition is called the glacial moraine. Where the glacier had carried either limestone and dolostone, the moraine was rich in calcium or magnesium. Where the glacier had carried shale and feldspar, the moraine was high in potassium-rich clay. The deposition of these various minerals is very random and sporadic across New York and is simply a function of whatever the last glacier was carrying and how rapidly the glacier melted. Often in southern New York, the glacier scraped the surface down to the bedrock and left little moraine behind. The resulting soils in this area tend to be thin and drought-prone. But in the northern Finger Lakes area of New York, the moraine is fairly deep with areas of exposed old lake bed soil and dried swamp areas. These soils today are deep, well drained, rich in minerals and highly productive.

Chemistry is not a subject that most people remember with great enthusiasm from their school days. However, to appreciate how the composition of soil influences plant growth, a little basic chemistry must be understood. In addition to farming 1000 acres organically with her husband, Klaas, raising 3 children, and writing articles for ‘Acres USA’, Mary-Howell Martens also teaches Biology and Plant Physiology at Finger Lakes Community College. Because chemistry is integral to understanding biology, this is a topic covered each semester in her classes and she presented a summary of basic chemical principles to the assembled group.

Ninety two naturally occurring elements have been identified on earth and these elements compose all matter, both living and non-living. Plants require only 16 of these elements for normal growth. Plants easily obtain carbon, hydrogen and oxygen from air and water, but all other elements must be supplied by the soil. These nutrient elements can be divided into 2 groups - those required in large amounts, the ‘macronutrients’, and those required in much smaller amounts, the ‘micronutrients’. The macronutrients include nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S). Since large amounts of macronutrients are required each year, they may need to be replenished through fertility amendments. The micronutrients are equally important to normal plant growth, but as they are needed in such small amounts, they usually are not deficient in most soils at pH of 5.0 - 8.0. Micronutrients include iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), boron (B), molybdenum (Mo), and chlorine (Cl). Cobalt (Co) is also required by the Rhizobium bacteria that colonize legume roots, and nickel (Ni) and sodium (Na) are required in minute quantities by some plant species.

An atom is the smallest possible particle of an element. Far smaller than microscopic, an atom is composed on a dense nucleus of positively charged particles called protons and particles called neutrons that carry no charge. Circling the nucleus are negatively charged electrons. For example, the nucleus of a sodium atom contains 11 protons and 11 neutrons. Outside the nucleus are 11 electrons. Since this atom of sodium has 11 positively charged particles and 11 negatively charged particles, they cancel each other out and the atom carries no net charge. The atomic weight, based on how many protons and neutrons are in the nucleus of an atom, determines how big the atom is. Hydrogen, with only one proton, is the smallest element. Sodium, with 11 protons and 11 neutrons, is about the same size as magnesium, with 12 of each. Calcium, with 20 protons and 20 neutrons, is nearly twice as large as magnesium.

The electrons are arranged in layers or orbitals, much like the planets in our solar system. The orbital closest to the nucleus can hold 2 electrons and the next two orbitals can hold up to 8 electrons each. Sodium, with 11 electrons, has 2 in its innermost orbital, 8 in its next orbital and only 1 in its outermost orbital. This is not a stable situation. Atoms that have less than 8 electrons in their outermost orbital will attempt to either lose or gain enough electrons to reach that number. If an atom loses an electron, as sodium usually does, it will then have more protons than electrons and will carry a net positive charge. If an atom adds electrons that other atoms have given up, it will then have more electrons than protons and will carry a net negative charge. In either case, an atom with either more or less electrons than its protons will carry an electrical charge and is called an ion, either a positively charged 'cation' or a negatively charged 'anion'. When an atom loses one electron, the resulting cation carries one positive charge. An example of this is the potassium ion, K^+. When an atom loses two electrons, the resulting cation carries two positive charges and therefore has twice the electrical positive power. An example of this is the calcium ion, Ca^{+2}.

Plant roots are only able to absorb ions. They are unable to take up nutrients that do not carry an electrical charge. In the soil, there are positively charged cations such as NH_4^+, K^+, Ca^{+2}, and Mg^{+2} and negatively charged anions such as NO_2^-, SO_4^{-2}, and OH^-. Soil is structurally composed of three different types of mineral particles that originally derive from the parent rock material. Sand has the largest size particle, silt is smaller, and clay has the smallest particles. A soil with approximately equal amounts of all three types of mineral particles is called a loam. Clay occurs in sheet-like particles with the clay surface carrying a negative charge. Cations will be attracted to the surface of a clay particle and will be held electrically, much like opposite poles of two magnets attract each other. Anions and clay particles, on the other hand, will repel each as will the two north poles of two magnets. Cations therefore are held securely by the soil clay particles, but anions are not. For this reason, anions have a greater tendency to leach or wash out of soil where there is nothing electrically holding them in place. Anions can be retained in a soil rich in organic matter, since humus particles hold both positively or negatively charged ions either by electrical attraction or by chemically combining with the ions.

In order for nutrients to be available for plant root uptake, cations and anions must be removed from the clay and humus particle surfaces and temporarily enter the soil solution. This is accomplished chemically. As plant roots grow, they undergo a process called respiration that allows plant cells to make energy available. A waste product of respiration is carbon dioxide gas. As the CO_2 gas leaves the roots and mixes in the soil, it has a tendency to acidify the soil solution. Decomposition of plant and animal material also has a tendency to make the soil more acid. This acidification releases quantities of hydrogen ions (H^+) that are strong cations with a powerful affinity for the clay particle surface. As the H^+ ions become attached to the clay particle, this removes some of the other cations which enter the soil solution. Suddenly these 'bumped off' ions are available for the plant roots to absorb. In simple terms, the ability of a soil to hold and then to release cations from the clay particles is called the soil's cation exchange capacity or its CEC. The soil pH and the soil mineral characteristics affect the CEC. Soils high in clay and organic material will typically have a higher CEC than sandy soils and therefore will usually to supply more nutrients to plants. On most New York soils, a CEC between 8-20 meq will probably be able to adequately supply plant nutrient needs. Extremely low CEC values may indicate a soil poor in nutrients and extremely high CEC values may indicate soil particle characteristics that hold nutrients too tightly for plant availability. Soils in other locations that are derived from other types of clay materials or muck soils that are composed of humus will have a different range of acceptable CEC values.

Soils are also sometimes evaluated on their percent base saturation. This is measurement of the relative proportion of different kinds of cations in the soil solution. Certain cations, H^+ and Al^{+3}, tend to acidify the soil solution, while the other cations such as K^+, Ca^{+2} and Mg^{+2} tend to make the soil more basic or alkaline. The base saturation of a soil shows what percent of the cations present are ones that make the soil more basic. In acidic soils, the base saturation tends to be low since the numerous H+ ions will adhere tightly to clay particles and many of the basic cations such as Ca^+ will be leached away. Liming a soil attempts to raise the base saturation by adding more of the basic cations, primarily Ca^{+2} and Mg^{+2}, to the soil matrix. The pH of the soil is raised by liming because some of the excess H^+ ions are displaced from the soil particles and they combine with OH^- ions in the soil to form neutral water. Basic cations are much more available for plant absorption in a soil with a high base saturation.

A useful way to visualize base saturation and cation exchange capacity is to think of the clay particle as a table. Around the table are a limited number of chairs. The actual number of chairs around each table will vary with the mineral composition of the soil. A soil with many clay particles will have more chairs while soil composed primarily of sand particles will have few chairs. The chairs may be occupied by either blue individuals (acidifying ions) or red individuals (basic ions), but when all the chairs are filled, the ratio of blue to red individuals is the percent base saturation of that soil. Now the situation gets more complicated. Some of those red individuals carry two positive charges, such as calcium and magnesium, and each one of them must occupy two chairs, thereby reducing the number at each table. There are also certain rude individuals who will come along, bump other ions out of their chairs and then grab the empty chairs for themselves. Hydrogen ions will do this, pushing other cations such as calcium out into the soil solution. The original number of chairs and the rate at which this bumping occurs is the cation exchange capacity of the soil. Small ions, such as hydrogen and sodium, allow the tables to be clumped close together, but ironically, while there may be more potential chairs with closer tables, now it harder for rude hydrogen to easily bump the other ions from their chairs and the CEC will drop. A compacted soil with poor drainage and poor structure is often one where small cations predominate. When the chairs are filled with large individuals, such as calcium and potassium, the tables tend to be pushed farther apart. As in any fine restaurant, tables that are farther apart make movement much more comfortable. Cation exchange capacity is increased, and the soil particles are more likely to form stable granules in a process called flocculation.

Phosphorus, another macronutrient, must be considered separately. Phosphorus is usually chemically combined with other elements in the soil to form molecules that plants are unable to absorb. Fortunately, certain microorganisms in the soil are capable to splitting these tough molecules apart and making phosphorus available to plant roots. Mycorrhizae, beneficial fungi that colonize the surface of plant roots, are particularly important in liberating phosphorus and assisting plants take it up. Any practice that adversely affects microbial populations in a soil will often also depress the level of available phosphorus. A soil that has been abused by chemical fertilizers and pesticides frequently has a small population of mycorrhizae, and plants may show phosphorus deficiencies if a chemical form of phosphorus is not supplied regularly. An organically farmed soil that has been carefully tended will be home to a large population of these beneficial organisms and much phosphorus will be readily available for crop growth. The pH of the soil affects phosphorus availability. At high pH levels, much of the phosphorus will be in the tricalcium phosphate form which is hard for plants to absorb. At low pH levels, phosphorus reacts with aluminum and other ions to form insoluble precipitates.

Three agricultural consultants shared their experience and perspective on soil chemistry and soil fertility. Dave Mattocks is well known in the organic community. He has been the president of the Fertrell Fertilizer Co., Bainbridge, PA. for the past 20 years and has worked extensively in agricultural consulting on soil fertility throughout the United States. Bob Hudak is a biological farming consultant with AgBioTech, Rochester. While he works primarily in central and western NY, he has consulted throughout the US, Canada and the Caribbean. Prior to this position, Bob was employed for over 30 years in nursery production and agricultural consulting. Rich Wildman owns and operates Agricultural Consulting Services, Inc., Rochester, serving the western and central NY area. While Rich works mainly with conventional farmers in New York, he sees high value in the cultural and fertility management practices that are more commonly used by organic farmers. They spoke about soil testing and fertility management.

All three consultants agreed that a soil test is only an approximation of the nutrients that will be available to a growing plant. No soil test measures the total nutrients in the soil. The results of a soil test are highly dependent on the method of chemical extraction. Rich Wildman stressed that there is no absolute right way to simulate the availability of nutrients and that the different extraction techniques all have validity. However, some methods may be more useful than others in a particular situation. It is important to understand the principles of different extraction methods and to select a soil testing lab that uses the most applicable technique to plan effective fertility management on a given farm. An acid extraction technique measures the potentially available cations over the entire growing season while a water soluble extraction method measures what nutrients are available to the plant immediately. Additionally, to assess phosphorus level, Bob Hudak generally recommends two specific types of acid extraction tests. The weak Bray extraction test predicts the amount of phosphorus that should be available to plants initially and the strong Bray extraction measures how much phosphorus will be available over the entire season. If the weak Bray test gives a low number, a starter fertilizer with phosphorus may be necessary. Although microbial activity has a tendency to release phosphorus naturally over the growing season, such activity may be slow in a typical New York spring under cold wet conditions. Since plants need to absorb phosphorus early and translocate it around the plant as needed, it is important to have ample phosphorus available at planting.

While the chemical components of a soil are important, Dave Mattocks stressed that it is essential to always consider fertility management as a way to feed the soil life, rather than simply feeding the plants. A healthy active soil microbial population is the key to producing healthy high yielding crops in a sustainable manner. Both Dave Mattocks and Bob Hudak subscribe to the fertility management approach called the Albrecht method. This states that the absolute amount of any nutrient in the soil that is less important than the ratios and interactions between different nutrients. For example, elevated phosphorus can make zinc less available, high nitrogen can induce a copper deficiency, high manganese can induce an iron deficiency and excess magnesium can tie up nitrogen and phosphorus. Imbalances in any nutrient can adversely affect both microbial life and soil structure, thereby reducing crop vigor.

The ratio eliciting the most comment and discussion was the relationship between calcium and magnesium. Many soils in New York are excessively high in magnesium, the result of being derived from eroded dolostone. Prior use of inexpensive dolomitic limestone, which is high in magnesium, has made this situation worse in many places. Excessive magnesium can increase soil compaction by cementing clay particles together, especially if the soil is worked while wet. Soil compaction causes numerous fertility imbalances. As air in the soil is excluded, the microbial activity is reduced and the available phosphorus plummets. In addition to being an essential nutrient, calcium causes soil particles to flocculate, increasing pore space and aeration. The three consultants suggested aiming for a 7:1 on a percent base saturation basis as an optimal calcium:magnesium ratio. This is equivalent to about a 10:1 ratio on the basis of pounds of calcium to pounds of magnesium. However, if the magnesium level is already high, it will require the addition of a very large amount of high calcium lime to achieve this ratio. If such large amounts of calcium are added, other nutrient imbalances may be caused by a sudden increase of pH in localized regions of the soil.

Many farmers therefore would like to be able to reduce the magnesium level in their soils without disrupting other nutrient relationships. The consultants suggested two approaches to reduce magnesium. The first approach would be to apply gypsum gradually at 250-500 lb/A for several years. Gypsum, $CaSO_4$, will dissociate in the soil solution. The SO_4 portion of the molecule will be strongly attracted to free Mg^+ in the soil, forming a relatively stable precipitate, $MgSO_4$ or Epsom salts, that is quite likely to leach out of the soil. The remaining Ca^+ ions will be able to replace the Mg^+ ions on soil clay particles. Because it takes time for the effect of gypsum to move down through the soil profile, applying larger amounts of gypsum at one time may throw off other nutrient balances or may remove excessive Mg^+ in the top few inches of soil where most plant rooting occurs. There are different types of gypsum available. Gypsum that has been fired or cooked is much more reactive than raw mined gypsum and therefore lower rates of fired gypsum will achieve the same results. Dave Mattocks stressed that the time of application is also important. Lime or gypsum applied in the fall will have a much greater influence on the next season's crop than if applied in the spring. The second recommended approach for removing excess magnesium is to plant a crop that accumulates large amounts of the ion. Such a plant is red clover. When red clover is used as a forage crop, it will absorb high levels of magnesium. This effectively removes the Mg^+ from the soil, and if the red clover hay is then fed to dairy cows, the Mg^+ will aid the cows' digestion. Any Mg^+ remaining in red clover crop residue will be tied up in fairly stable chelates that will not adversly affect the soil for several years. Rich Wildman cautioned that while these approaches can improve some fields, there are locations in New York where magnesium levels are not excessive and the use of gypsum might actually induce a magnesium deficiency. Dave Mattocks stated that all lime is not created equal and that any farmer ordering a load of lime should specify whether high Mg or low Mg lime is desired.

The effect of cultural practices on soil fertility should not be ignored. The amount of pore space in a soil is critical, since movement of air and water through the soil is essential to microbial activity and vigorous plant rooting. Soil aeration is probably the most important factor in the depth of plant rooting, since roots require oxygen for respiration. Microbial populations change when soil air is excluded, pathogenic anaerobic fungi that can survive without oxygen will rapidly increase and certain weed species may also become more prevalent. Crop species vary in their soil aeration requirements. Beans and peas will die within 2-3 days if aeration is limited, while rice can grow well in saturated soil. Rich Wildman stressed that soil aeration can be improved by paying attention to the factors that cause compaction. These include the type and timing of tillage, the amount of crop residue and organic matter, the level of soil moisture especially during field operations, and the soil type. A soil high in silt and sand is likely to become compacted if tilled with heavy equipment when wet because the fine silt particles can easily slide into the spaces between sand particles and exclude air. Soils high in clay will often show poor flocculation and can also become hard and compacted. The addition of organic material to either type of soil will improve resistance to compaction. Wildman spoke of a field of corn he observed this season. The corn was weak with shallow brittle roots that extended only about 3 inches into the soil. This field had been tilled with a field cultivator with sweeps when the soil was too wet. This operation had formed a very thin but impermeable compacted layer that the plant roots were unable to penetrate. It was emphasized that this was a conventionally farmed field. This situation would be much less likely on organic fields under a carefully planned crop rotation that would leave adequate of crop residue in the soil, but it important to realize how seemingly beneficial field operations can adversely affect crop growth.

As the meeting concluded, it became apparent that soil chemical composition and soil fertility management is a far more complex topic than most of the participants had realized. There is much more to fertility than simply applying chemical inputs. Organic farmers can not afford to ignore the intricate interactions between the soil physical characteristics, the microbial life, and the resulting availability of nutrients. There is a vast reservoir of valuable nutrients present in most soils. Soil tests can predict the nutrients potentially available, but soil tests are of no value unless they are used to plan appropriate fertility management. Through careful attention to the biological life of the soil and to the physical soil structure, reliance on expensive outside inputs can be minimized. Healthier plants result from healthier soil.