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Introduction

Why is soil Important? Soil is the foundation upon which we build plants. Whether you are establishing a new planting or managing existing plantings, it is essential that you learn all you can about the soil beneath your plants; a strong "soil foundation" means strong plants, a weak foundation means weak plants. Poor soil conditions not only translate into slow plant growth and numerous plant physiological problems, they can also increase plant stress making plants more susceptible to pest and disease problems.

*"A trees leaves may be ever so good, so may its bark, so may its wood;
But unless you put the right thing to its root, it never will show much flower or fruit."*
-- Robert Frost

Soil is also the **Great Integrator** of all parts of terrestrial ecosystems; it is an *essential natural resource*. This powerful statement is undeniable given the catastrophic consequences reaped from the destruction of our soils.

"Essentially, all life depends upon the soil ... There can be no life without soil and no soil without life; they have evolved together." -- Charles E. Kellogg, USDA Yearbook of Agriculture, 1938

The "Dust Bowl" provided an instructive example of what happens when we ignore the importance of protecting soils. Poor agricultural practices, fragile soils, and intense drought conspired to create a perfect ecological and sociological storm with consequences that rippled across the United States. Also known as the "Dirty Thirties," America's Great Plains were repeatedly raked throughout the 1930's by devastating dust storms; there were 14 major dust storms in 1932 alone. In May, 1934, a dust storm that originated in the Great Plains re-deposited a dusting of topsoil 1,500 miles away from Maine to Georgia.

Known as the “Great Dust Storm of 1934”; a small amount of dust settled onto the White House desk of Franklin D. Roosevelt.

“A nation that destroys its soils destroys itself.” -- Franklin D. Roosevelt

The destruction of highly productive soils in the Great Plains not only changed agriculture; it changed the face of the entire United State. By 1940, 2.5 million people had moved out of the Plains states; of those 200,000 moved to California.

(<http://www.pbs.org/wgbh/americanexperience/features/general-article/dustbowl-mass-exodus-plains/>)

Soil Formation

Where does soil come from? Your soil may have originated from someplace else. Soils that were deposited by the wind are called **aeolian** (eolian) soils, named for Aeolus the Greek God of the wind. One of the most commonly recognized aeolian soil is loess. This highly fertile wind-blown soil has a high percentage of silt and is not common to Ohio. Another type of aeolian soil are the sandy soils found in the western part of the state. While their origins are traced to ancient lake shores, their ultimate destinations were determined by the wind.



Figure 1: Aeolian Sand Soil

Soils that were deposited by the movement of water are called **alluvial** soils. These soils are found along streams, waterways, and in river deltas. Alluvial soils are common in Ohio River valleys as well as in locations where water flowed from ancient glaciers. These water-deposited soils tend to have high silt content because heavy sand particles settle quickly from flowing water while the extremely small clay particles may remain



Figure 2: Alluvial Soil Deposit

suspended for hundreds to thousands of miles.



Photo by Bernard Spragg

Figure 3: Glacier



Photo by Jacki Stark

Figure 4: Glacier Groove on Kelly's Island

Glaciers advanced and receded across large areas of North America including Ohio. Although the last Ice Age ended around 10,000 years ago, the effects of these gigantic earth movers remain evident today. Glaciers were capable moving earth material of all sizes from tiny clay particles to huge boulders, thus "glaciated soil" is represented by a wide array of soil types.

Glaciers acted both like enormous bulldozers by shoving soil ahead or as conveyer belts by transporting material trapped on top or within the ice. The result is "glacial till" (moraine) which includes all particle sizes including large stones. Where glacial meltwater moved material just like a river, the result is "glacio-fluvial" soil which is analogous to alluvial soils. Where glaciers formed lakes, the resulting soil is termed "glacio-lacustrine" which is comparable to "lacustrine" soils comprised of particles the settled to the bottom of ancient lakes. In short, glaciation had a dramatic effect on soil formation, so it is very important to learn whether or not your soil was affected by these icy earth movers.

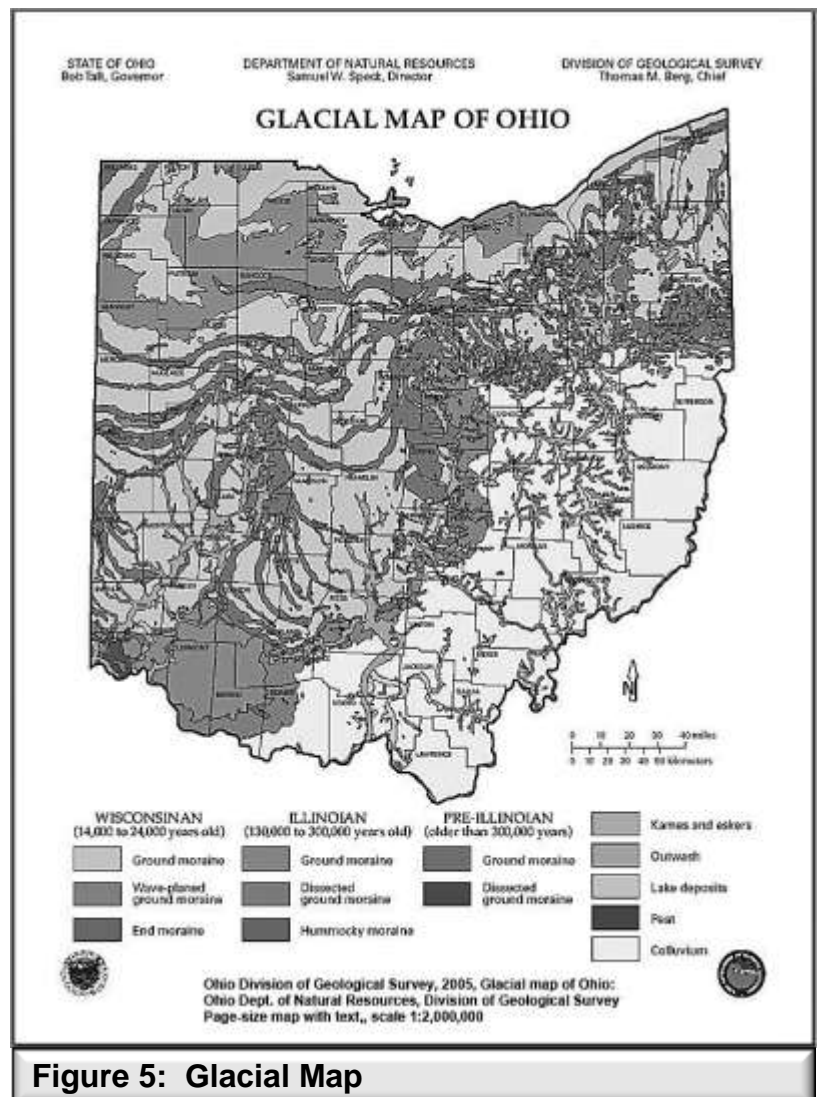


Figure 5: Glacial Map

Local geology also influences soil formation. Figure 6 shows an outcrop of Sharon Conglomerate which is found in many areas of eastern Ohio. The conglomerate consists of combination of quartz and tightly compacted sand. It's not coincidental that soils in proximity to this formation tend to be high in sand. Such rock outcrops are an important source for sand, silt, and clay; the basic mineral components of soil. Indeed, soil is geology, and geology is soil.

Whether or not your soil arrived from someplace else, or it was created on-site through slow geological, chemical, and biological processes that occurred over tens or hundreds of thousands of years, those same soil-forming processes remain active today. Indeed, soil formation is an on-going dynamic process; it never stops.

“Most of all one discovers that the soil does not stay the same, but, like anything alive, is always changing and telling its own story. Soil is the substance of transformation.” -- Carol Williams

Soil forms naturally from the top-down and from bottom-up. Organic matter is constantly moving downward in the soil profile; leaves dropping from current trees ultimately become part of the topsoil that grows future trees. Conversely, mineral material found deep beneath the soil surface is constantly moving upward in the soil profile.

Although this soil-formation conveyor belt would seem to defy gravity, bedrock deep beneath the surface is constantly fracturing to become the parent material above and the parent material is constantly weathering to become subsoil and the subsoil is constantly further weathering and mixing with organic matter (from above) to become topsoil. Ultimately, the bedrock contributes to the topsoil layer. Thus, if the bedrock is limestone, the topsoil layer will have a high pH.

Soil Properties

There are three soil properties that are used to describe the general characteristics of soils. These are:

- **Physical Properties:** this includes the way soil is deposited in layers (horizons) as well as the way the soil "feels" (texture) and how it is constructed (consistency and structure).
- **Chemical Properties:** soil chemistry drives many of the nutrient characteristics of soil that are important to plant health, such as pH and Cation Exchange Capacity (CEC).

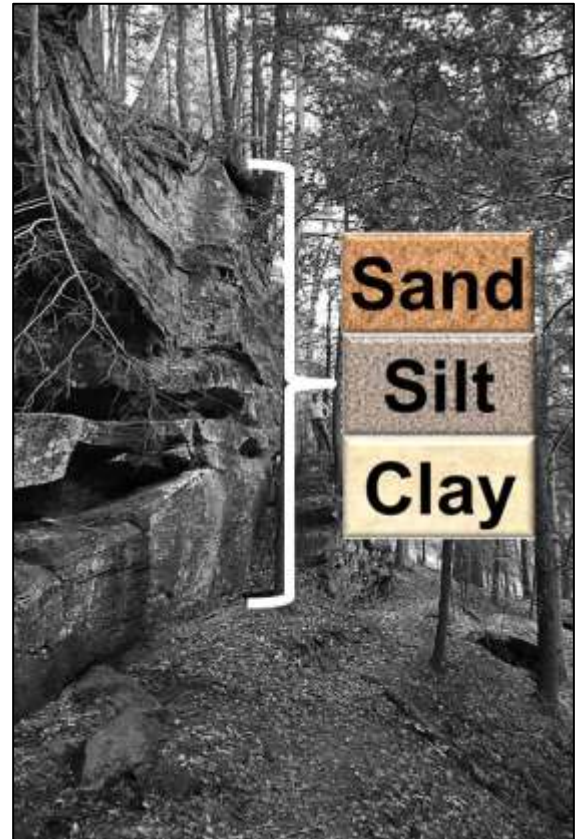


Figure 6: Sharon Conglomerate Rock Outcrop

- **Biological Properties:** the soil is home to a menagerie of micro- and macroorganisms that exert great influence over the way the soil supports plants.

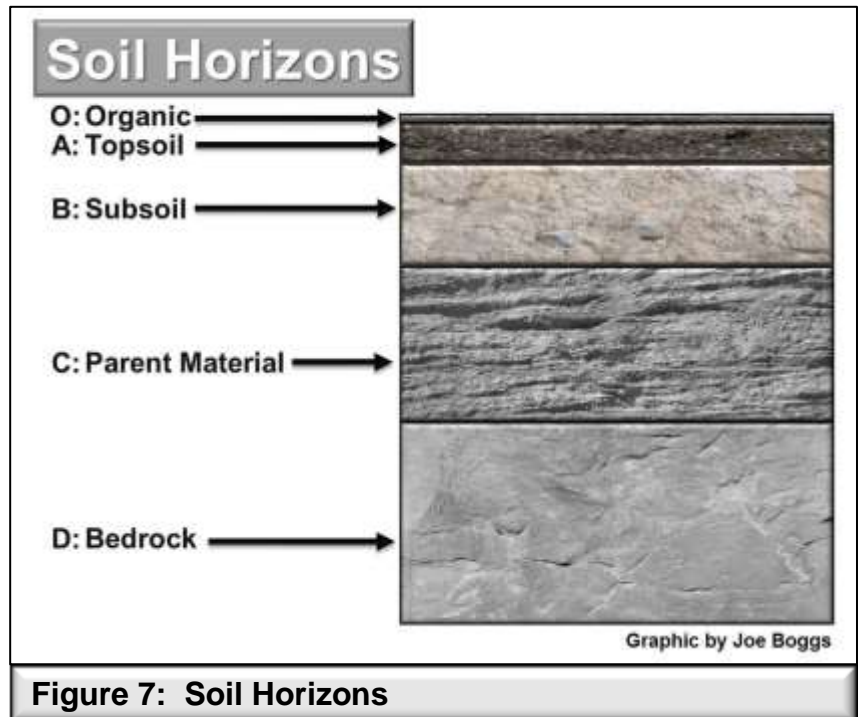
It is very important to understand that components of these soil properties interact to influence the ability of soils to support healthy trees.

For example, soils that are high in clay (a physical property) have a greater ability to hold certain nutrients (a chemical property). Conversely, a high percentage of clay reduces soil drainage which influences the types of organisms (a biological property) that can live in the soil.

Physical Properties of Soil

Horizons

We cannot see into the soil; however, what lies beneath our feet is clearly made visible in deeply excavated trenches or where highways slice through hills. Both provide a window into the local geology revealing different aged strata; the newest layers are nearest the surface, the oldest layers are the deepest. The cross-section of the strata usually looks like a layer cake. Soil scientists refer to each layer as a "**Soil Horizon**" (Figure 7). Although the term "soil" is generally reserved for the uppermost horizons (topsoil, subsoil), even the deepest horizons are still considered soil horizons because they continually influence soil formation.



Remember that soil is formed from bottom up as well as the top down. It is easy to visualize organic matter dropping down from plants to contribute to soil formation. However, mineral matter is constantly being contributed to the soil mix by moving up from rock buried beneath the surface. Thus, topsoil (Horizon A) in Ohio is typically comprised of organic matter from plants as well as mineral particles (sand, silt, and clay) from beneath.

There is no official, regulated definition for topsoil; it is the soil on top. It is important to know something about local sources of topsoil. A topsoil harvested a short distance from the site is likely to have the same characteristics as the topsoil found on the site.

This is not a problem if the local topsoil has desirable characteristics and is being used to replace lost topsoil. However, if soil improvement is the goal, the quality of purchased topsoil becomes an important consideration.

It is also important to have a clear understanding of the horizons lying beneath your soil. For example, knowing that the bedrock and "parent material" horizons are composed of limestone or if they are rich in calcite will have a significant impact on your landscape designs and plant selection. **Limestone** and **calcite** both share the same chemical names (**calcium carbonate**) and chemical formulas (CaCO_3). Limestone formed millions of years ago as a result of the shells of marine organisms that were made up of calcium carbonate settling to the bottom of lakes or oceans; limestone is known as a "**sedimentary rock**." Calcite formed through chemical processes that caused calcium carbonate to crystallize. Limestone and calcite will both cause pH to rise or become **alkaline** (= basic).

If the bedrock and parent material horizons are limestone or calcite, the pH of the topsoil overlaying these horizons will naturally rise to become alkaline over time. Plants that grow best in acid soils would be a poor choice under these conditions. Conversely, plants that do well in alkaline soils would be a good choice. What lies beneath your feet needs to be considered before you make plant selections for your landscape!

Trouble on the Horizon

Some soil problems arise from past practices. The past history of the soil may provide insights into current soil problems and help to guide you with developing possible solutions. Was the land re-graded? Was the land plowed year after year to grow crops? Ask neighboring land-owners if they know the past history of your plot: be a "soil detective."



Figure 8: Limestone



Figure 9: Soil Damaged by Construction

Soil Compaction: Soil compaction occurs anytime heavy equipment has been driven over the soil. This includes construction equipment driven over the soil during home construction as well as vehicles or equipment driven over the soil to plant trees, install fencing, etc. Soil compaction is a condition where the soil is compressed to the point where large spaces (macropores) are squeezed shut (Figure 11). The spaces are important for holding air and for allowing water to drain through the soil; consequently soil compaction affects water drainage and root health by reducing the availability of oxygen to root cells. It is important to remember that compacted soils still retain all of the components of the original topsoil! Thus, while compacted soils have been damaged, they still have all the ingredients that can make it possible for the soil to be repaired; it will just take time. Of course, the time required to "heal" the soil may affect the ability to grow healthy trees, shrubs, and turfgrass.

Topsoil Removed: If the topsoil (Horizon A) has been removed during past re-grading, the subsoil (Horizon B) will constitute the exposed soil layer. Exposed subsoils are often mistaken for compacted topsoil; however, it is important to accurately identify the problem because the solution is usually more costly compared to dealing with compacted topsoil. Subsoils in Ohio are typically very poor substitutes for topsoil and using them as topsoil seriously limits the sustainable growth of most preferred plants.

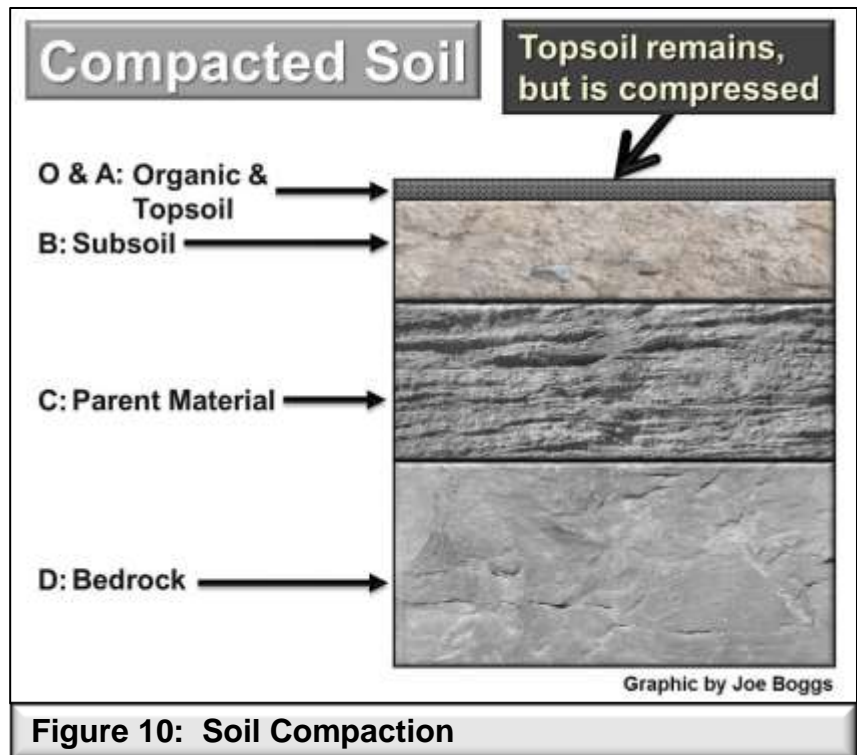


Figure 10: Soil Compaction

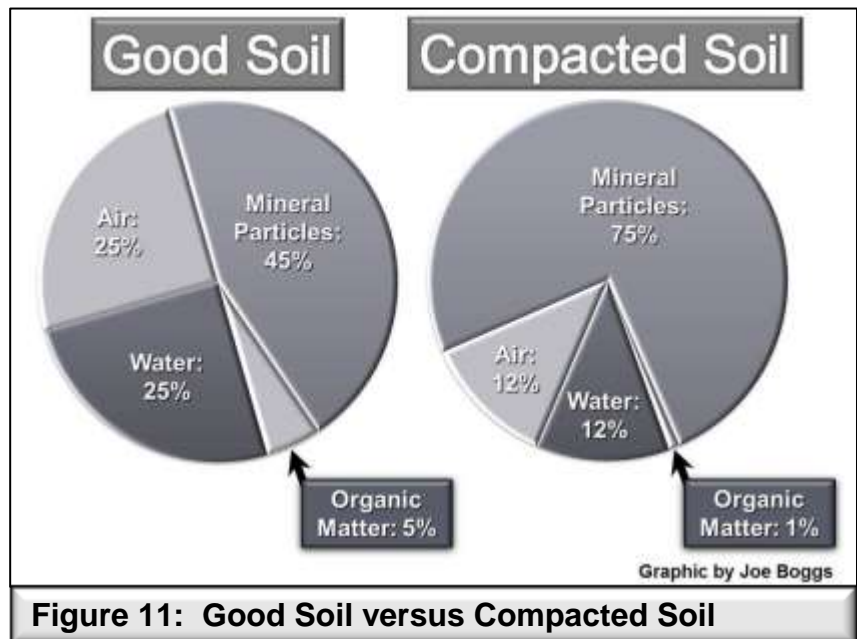


Figure 11: Good Soil versus Compacted Soil

If the topsoil has been removed, there is little that can be done to repair the damage. It would take many years, perhaps hundreds of years, for the subsoil to evolve to become acceptable topsoil even with the introduction of organic matter. The most practical recommendation for correcting the problem is to redistribute topsoil over the site; ideally to the same depth as the original native topsoil.

Of course, the new topsoil should be assessed to make certain it is of good quality and compatible with the subsoil. For example, if the subsoil is composed of sand-based material, topsoil with high clay content will produce a soil incompatibility problem. The new topsoil should also contain organic matter. If the topsoil has been removed, the organic layer (Horizon "O") has also been removed.

Built on a Farm: There are two soil problems that may have developed over time as the result of continued cultivation for annual crops. Both problems are often mistaken for the subsoil (Horizon B). Repeated plowing can produce a **soil compaction zone** where the bottom of the plow compressed the soil as it moved through the soil. Compaction zones are usually around 7" to 9" beneath the soil surface.

Plowing also churns and loosens soil. A **false "clay horizon"** occurs when the small clay particles in the loose soil are moved downward by water through the soil profile. There are two terms that are used to describe the particle movement and the result:

- **Eluviation:** the downward movement of soil particles by water.
- **Illuviation:** the deposition of soil particles into a lower soil horizon. This creates a "false horizon" that is composed of the deposited clay particles.

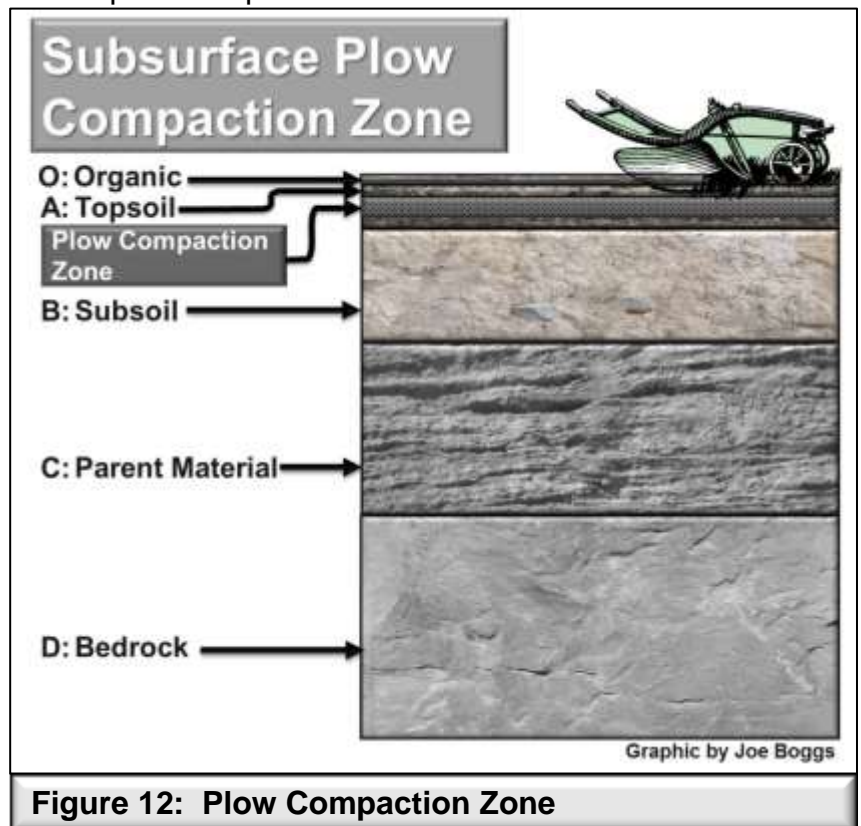


Figure 12: Plow Compaction Zone

Soil compaction zones and false clay horizons are corrected with agricultural crop production using a **subsoiler** (= mole plow). A subsoiler is an implement that is made-up of one or more knife-like "shanks" that cut deep into the soil to breakup compacted soil or to loosen false horizons. However, subsoiling is almost never performed by contractors or developers before or after construction of homes or buildings.

Soil Testing

No other tool provides more helpful information on soils than a **soil test**. Soil tests are used for three purposes:

1. A maintenance tool to make certain important soil parameters (e.g. nutrients) are being maintained within prescribed ranges necessary for sustaining healthy plants.
2. A plant selection tool to guide you in deciding which plants to use in a landscaping. For example, if your soil has a high pH, it's best not to select acid loving plants.
3. A diagnostic tool to help you determine what is wrong with plants in a landscape or vegetable garden. For example, if trees are exhibiting yellowing (chlorotic) leaves during the growing season, a soil test will help you to determine if the problem is related to soil pH or if the nutrient is lacking in the soil; or both!

Soil tests are conducted on small amounts of soil, usually around 1 pt. in volume, being sent to a soil testing laboratory. Soil samples can be collected using a shovel or hand trowel; however, Figure 13 shows two types of soil probes that make the job much easier. Soil probes are also helpful with monitoring soil moisture and even assessing soil compaction.

Most soil testing laboratories will provide specific recommendations on how you can maintain sufficient nutrients in the soil to support good plant health or how you can correct pH problems and nutrient deficiencies.

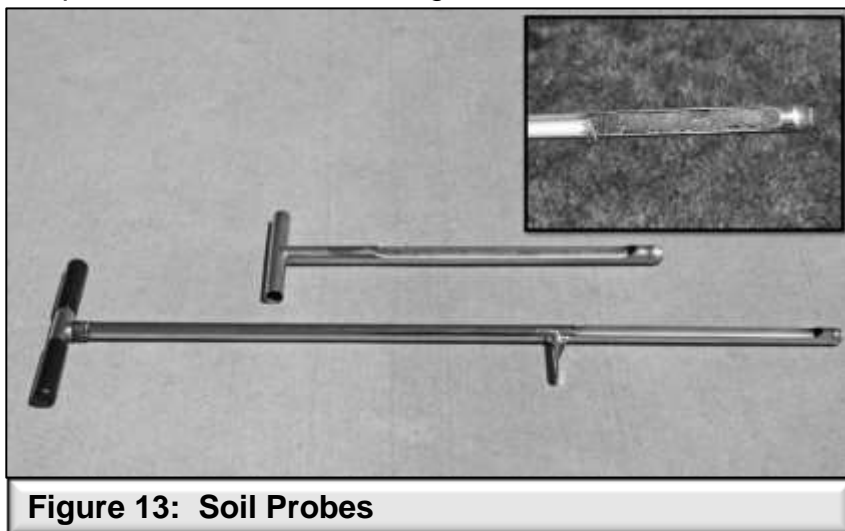


Figure 13: Soil Probes

Soil Texture

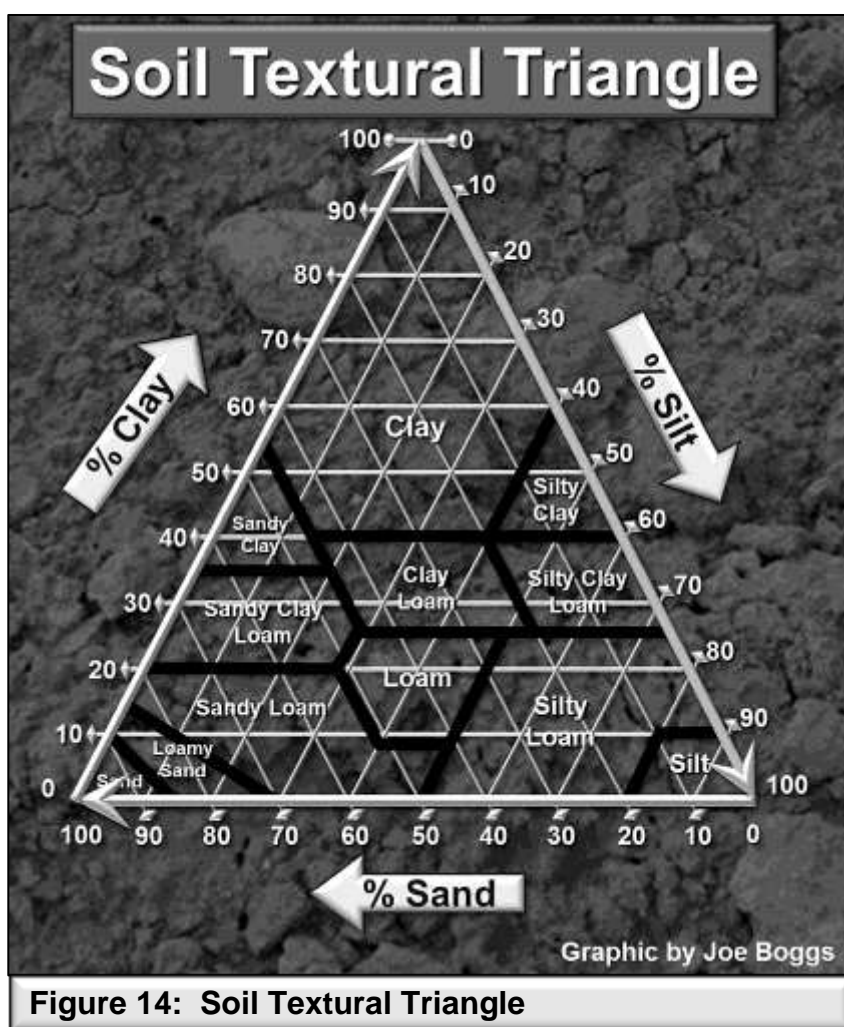
Soil scientists use sieves or screens to separate soil particles into three size classes: sand (large particles), silt (medium sized particles), and clay (smallest particles). These are called the "mineral components" of the soil and they are entirely defined by the diameter of the particles. There are a number of different systems used to define the mineral components of soil based on particle size; however, the following particle classification system is used by the United State Department of Agriculture (USDA) and is the most common system used by soil testing labs:

- **Sand:** 2.00 - 0.05 mm; the largest particles, they feel "gritty".
- **Silt:** 0.05 - 0.002 mm; medium sized particles, they feel soft, silky or "floury".
- **Clay:** < 0.002 mm; the smallest sized particles; they feel "sticky" when wet.

The **Soil Textural Triangle** shown in Figure 14 is used to assign a soil textural classification (textural types) to a soil. Once the relative percentages of sand, silt, and clay are known, the triangle is used to find where the soil "fits" among the textural types. For example, a soil that has 40% sand, 40% silt, and 20% clay would be classified as a "Loam."

Loam is generally considered to be the best soil texture for plant growth while clay is often maligned as the least desirable mineral component of the soil. However, note on the Textural Triangle that loam soil may contain as much as 27% clay! This illustrates that the best soils have a helping of all three mineral components. It is also important to remember that the only way to change soil texture is to change the relative percentages of the three mineral components of the soil.

What about Gypsum and clay soil? Gypsum is Calcium Sulfate (CaSO_4) and it affects the soil by acting on chemical properties, not by changing the physical properties of soil. The idea that gypsum can improve clay soils is based on a misunderstanding. Soils that contain high concentrations of salt (sodic soils) behave similar to soils that contain a high percentage of clay; they both become sticky when wet. Gypsum can improve sodic soils by inducing chemical reactions that release mineral salts from the soil particle; however, it does not change the actual percentage of clay in the soil. On the other hand, gypsum is an excellent source of calcium and unlike lime-based calcium sources such as dolomitic lime [$\text{CaMg}(\text{CO}_3)_2$], gypsum will not affect soil pH.



Soil Texture and Water

This graph shown in Figure 15 is frequently used in soil textbooks and manuals to illustrate the relationship between soil texture and soil moisture. The amount of water in the soil is plotted on the x-axis of the graph while soil particle size (texture) is plotted on the y-axis. Following are the definitions of the terms used on the graph:

- **Gravitation Water:** the water that will drain from the soil by gravity. Imagine holding soil that is saturated with water up in the air. The water that drains from the soil by gravity is descriptively named gravitational water.
- **Field Capacity:** the water that remains in the soil after it has been drained by gravity.
- **Water Available to Plants:** the water that is held in the soil against gravity, but is able to be transferred from the soil into the roots of plants.
- **Permanent Wilting Point:** water in the soil that is so tightly bound on the surface of soil particles that it is not available to plants.
- **Unavailable Water:** the range of soil moisture levels where some water remains in the soil but it is held too tightly to the surface of soil particles, particularly clay, to be available to plants to the point where the soil is practically devoid of all water. Note the differences between sandy soils and soils high in clay. This partially explains why drought has a greater and more rapid impact on plants growing in clay soils compared to sandy soils.

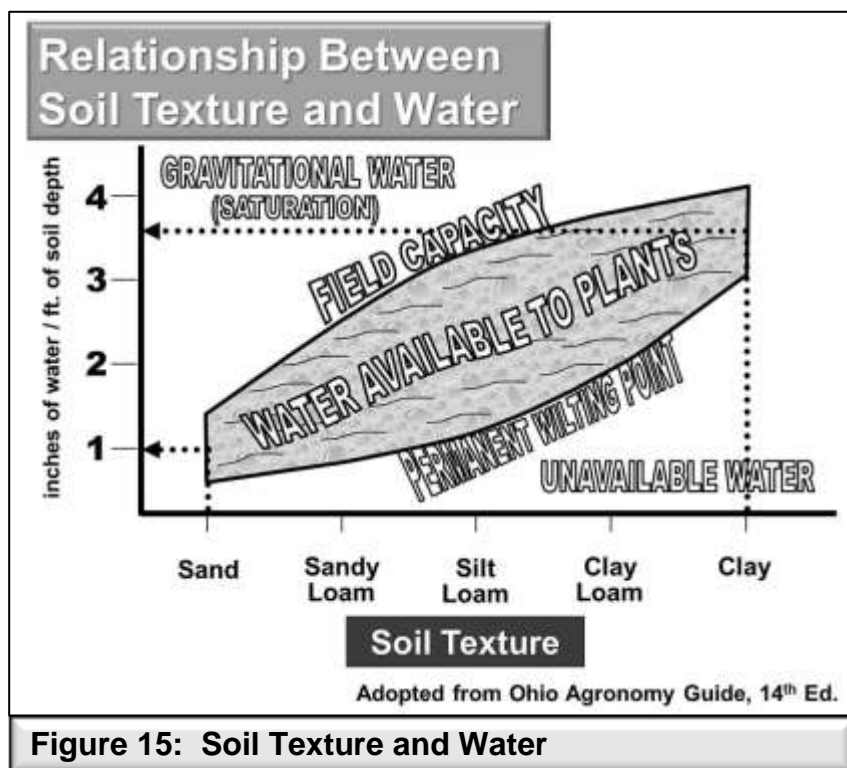


Figure 15: Soil Texture and Water

At first glance, the information presented on the graph appears straight forward. After all, the fact that sand drains faster than clay is common sense. However, this is not the most important soil feature that is depicted on the graph. Remember that it is only "gravitation water" that drains from the soil. The "Water Available to Plants" refers to water that is being held in the soil against gravity. What is keeping the water from draining from the soil and why does clay hold onto more water compared to sand and silt?

Part of the answer is related to particle size. Water is held on the surface of soil particles; it does not penetrate individual sand, silt, or clay particles. Smaller particles have a greater surface-to-volume ratio compared to larger particles. This means that a collection of small particles (clay) will have a greater total surface area to hold onto water compared to a collection of large particles (sand). To imagine how this works, consider how we might increase the surface-to-volume ratio of a table (Figure 16). By cutting the table into pieces, we create smaller table "particles," and we've exposed a larger surface area compared to the original table. The un-cut table would represent sand particles while the small pieces of the cut-up table would represent clay particles.

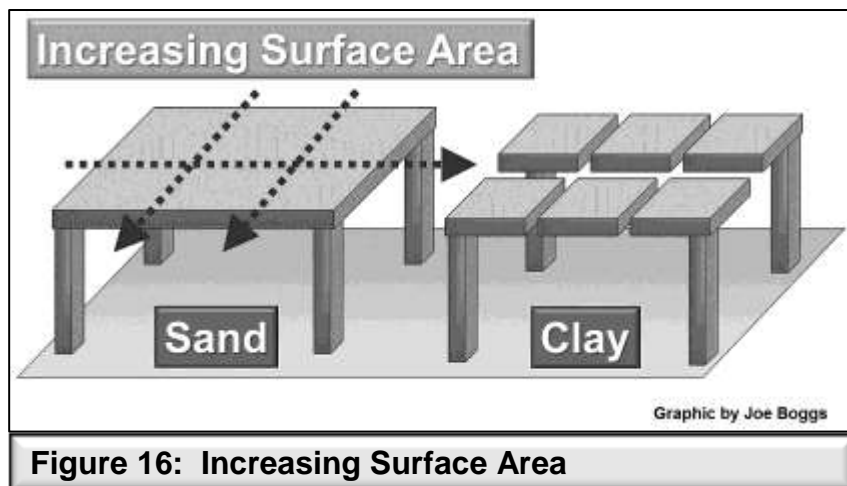


Figure 16: Increasing Surface Area

The second reason clay holds onto more water compared to sand and silt is more subtle. It is related to chemical characteristics of water coupled with certain physical characteristics of clay. We will answer this part of the question after we examine some basic principles of chemistry.

Chemical Properties of Soil

Remember that the three properties of the soil (physical, chemical, and biological) interact to influence soil characteristics. To fully understand how soil texture influences the soil's water holding characteristics, it is important to first understand how soil chemistry is affected by soil texture.

The Strange Properties of Water

Figure 17 illustrates that a water molecule consists of an oxygen atom (O) that is attached to two hydrogen atoms (H₂), so the chemical formula for the water is H₂O. The oxygen atom is an anion; it has a negative electrical charge. The hydrogen atom is a **cation**; it has a positive electrical charge. While the H and O atoms are attracted to one another because they have opposite charges, the water molecule is held together by

the H and O atoms sharing electrons. This is called a **covalent bond** and it is much stronger than an **electrostatic bond**, the kind of "bond" that can be illustrated by joining opposite ends of bar magnets.

The entire water molecule has a very strange electrostatic property based on the inherent electrical charges of the hydrogen and oxygen atoms. The two hydrogen atoms impart a weak positive charge to the hydrogen side of the molecule, while the oxygen atom imparts a weak negative charge to the oxygen side of the molecule. This causes the water molecule to be **bipolar**.

The bipolar nature of water molecules means the molecules behave just like tiny bar magnets, each with a positive end and a negative end. Water molecules can attach to one another, just like bar magnets. This electrostatic bond is a very weak type of attachment; however, this strange nature of water explains **surface tension** and is illustrated (Figure 18) by water droplets beading-up on a flat surface. **Capillary attraction** is responsible for the transport of water up the vascular systems of plants; without it, water could not translocate from the roots to the very top of huge trees.

The Strange Properties of Clay

Clay particles have distinct sites on their surface that are negatively charged. Remember that clay particles are the smallest mineral particles in the soil and the negative charge of these sites occurs at the

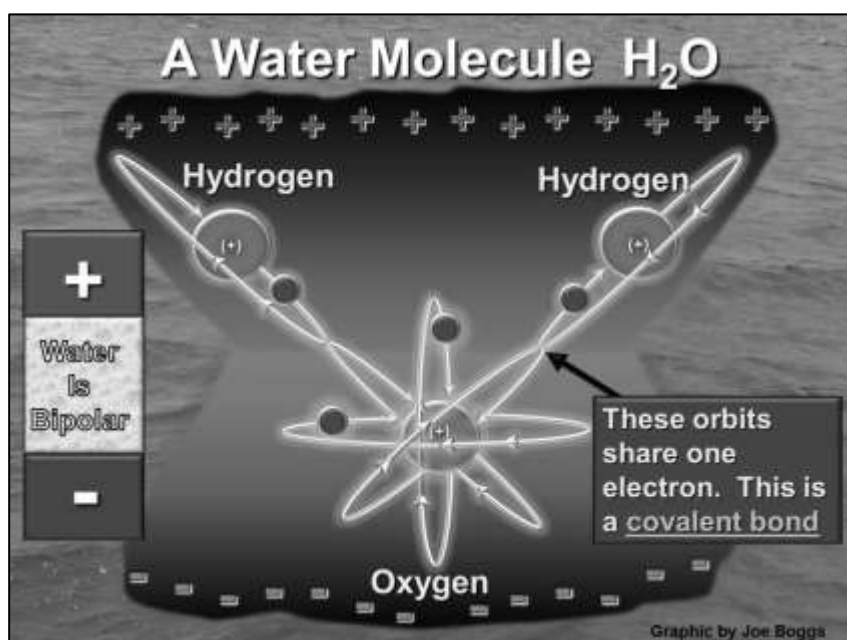


Figure 17: A Water Molecule

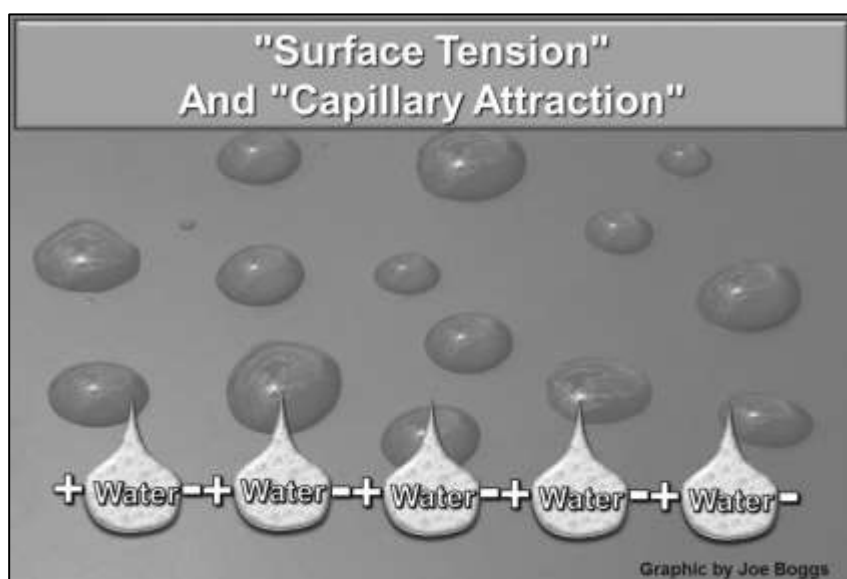


Figure 18: Water, Surface Tension, and Capillary Attraction

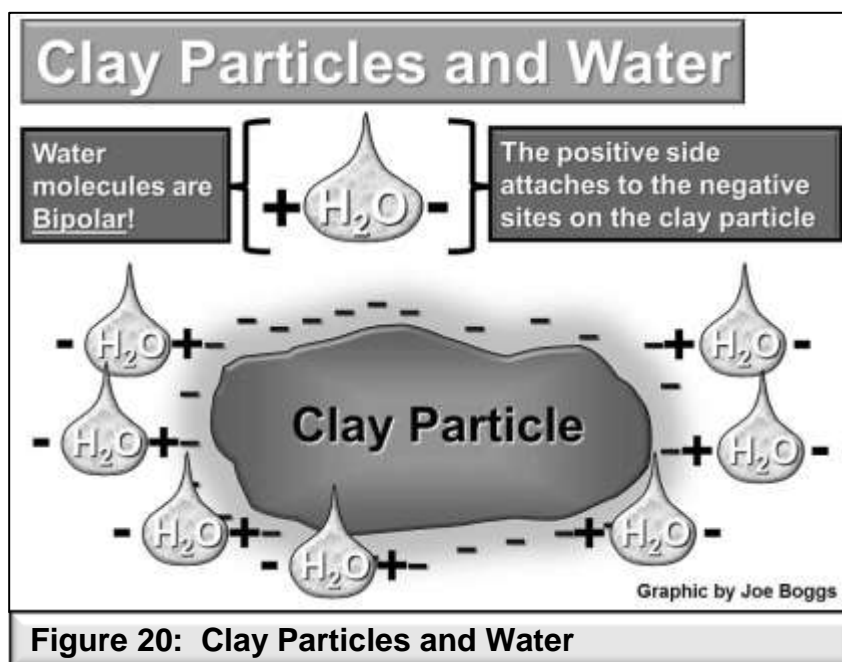
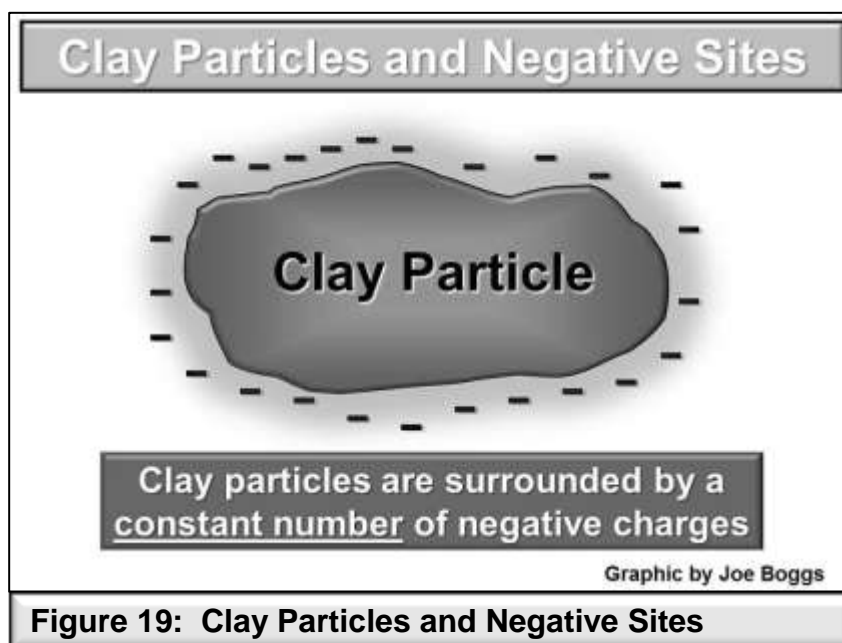
atomic level; the charge is associated with crystalline nature of clay. There are a constant number of charges on each clay particle (Figure 19). The only way to change the number of charges is to fragment the clay particle which requires far more pressure than can be exerted on clay particles outside of a laboratory.

What do the negatively charged sites on the clay particles mean to the relationship between clay and water? Figure 20 illustrates that the positive ends of the bipolar water molecules attach to the negative sites on the surface of the clay particles. Thus, clay holds onto more water compared to sand and silt because of electrostatic forces and because clay has a larger surface-to-volume ratio.

What does the relationship between soil texture and soil water holding capacity mean to you? The differences in the way the small clay particles and the much larger silt and sand particles hold onto water means that water movement is disrupted when soils with drastically different particle sizes are placed next to one another. The problem is called **soil incompatibility**, and the outcome can have dramatic consequences.

For example, trying to improve the drainage of clay soils by adding topsoil with a high sand content will have a limited impact because water infiltrates clay much more slowly compared to

sand. Conversely, if clay soil is inadvertently placed over a sandy soil, water will remain attached to the clay particles and will not flow into the sand. In both cases, a **perched water table** may be created meaning that water remains trapped near the surface giving the false impression that the soil is saturated throughout its profile. A perched water table can have a significant negative



impact on plant root health by keeping roots submerged in water for a longer period of time than would otherwise occur based on the original soil textural profile.

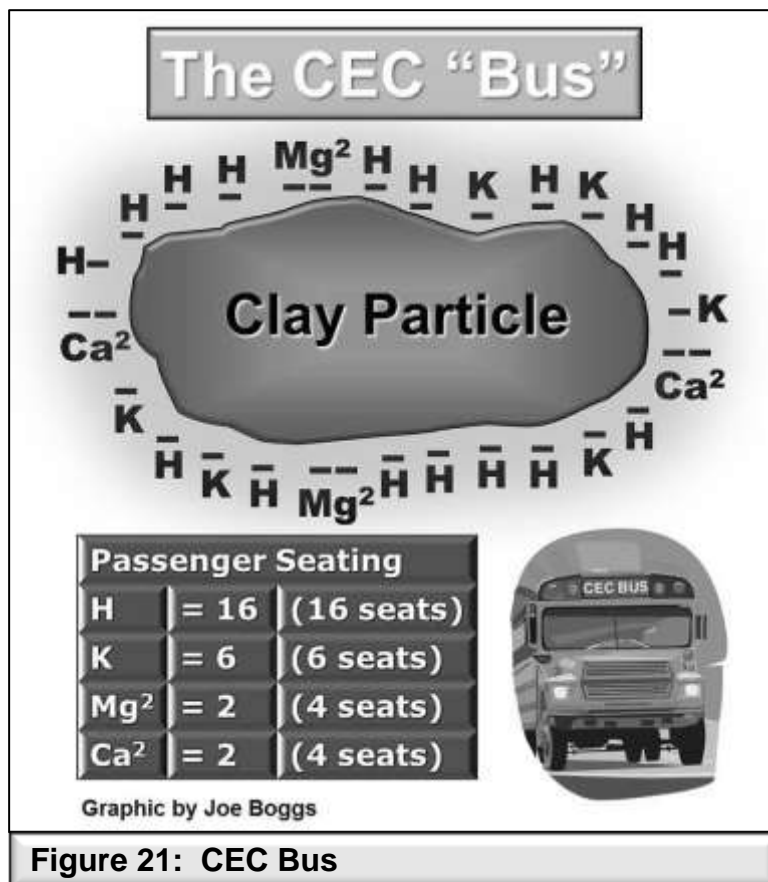
Cationic Exchange Capacity (CEC) and the CEC Bus

The negative charges on the surface of clay particles also play an important role in holding nutrients in the soil. As noted, each clay particle has a specific number of negatively charged sites and the number of negatively charged sites on each particle does not change; it remains constant no matter what is done to the soil. We can illustrate the constant nature of the number of negatively charged sites on a clay particle by comparing the sites to the number of seats on a bus; the number of seats does not change as the bus moves down the highway!

Many of the nutrients that are important to plant health are **cations**; they are positively charged. The cations become the passengers on our "CEC bus" by attaching to the negative sites on the clay particles; these are the "bus seats." The cations are attached onto the clay particles by electrostatic bonds which are exactly the same as the weak connection between the opposite ends of bar magnets. Electrostatic bonds are not the same as chemical bonds; the bar magnets do not become welded together! In the same way that bar magnets can be easily pulled apart, the plant nutrient passengers can easily disembark from the CEC bus.

While understanding CEC starts with visualizing each soil particle as a bus with a constant number of seats, the total CEC of a soil is not based on a single soil particle; it's based on the total number of negative sites on all of the particles in the soil. It's just like counting the total number of seats in a whole fleet of buses to determine how many passengers can be carried by the entire bus fleet!

We have been focusing on a clay CEC bus because clay particles have the most



number of negative sites - the most seats - compared to silt and sand particles. Indeed, sand particles have very, very few CEC seats. Thus, in a roundabout way, the CEC of a soil is also a measure of soil texture for "mineral soils;" these are soils with a percentage of sand, silt, and clay. Typically, the higher the CEC number, the higher the percentage of clay in the soil and the lower the CEC number, the lower the clay content. Of course, this only holds true for mineral soils.

What does CEC mean to you? The higher the CEC, the higher the soil's capacity to hold onto nutrients; the nutrients are not easily washed through the soil by water. Conversely, a low CEC number means nutrients can be easily washed from the soil by water. This is why potting soils (e.g. "soil-less media") that contain no clay will not hold onto nutrients. The nutrients must be continually added in order to grow healthy plants. The answer to the age-old question, "is clay bad for the soil?" is a resounding "No!" Clay acts like a nutrient sponge to hold nutrients until they are needed by plants.

What about CEC and **rain gardens**? Rain gardens are landscape installations that are designed to slow both the volume and flow rate of rain water issuing from a site. They and other landscape designs, such as "bioswales," are used to solve several problems including flooding, soil erosion, and water pollution. Rain gardens are not the same as wetlands; the intent is to slow water movement, not to collect water. It is also important to remember that as with any landscape design, rain gardens should contribute to the overall aesthetics of landscapes. Thus, their designs should support sustainable plant growth.



Figure 22: Rain Garden

A common rain garden design feature involves the use of sand beneath the garden because of the predictability of water drainage through sand. However, sand has almost no CEC; so what happens to plant nutrients? As with soil-less media, there is nothing to hold onto plant nutrients. This presents two challenges. First, sustainable plant growth requires that additional plant nutrients are applied to a sand-based rain garden to offset the nutrients being washed from the garden. The second challenge is the risk to water quality presented by the nutrient-rich discharge being washed off site into drainage systems and waterways.

The use of native plants is another common rain garden design feature. However, there are few areas in Ohio where native plants evolved in sand-based ecosystems. Selecting plants for sand-based rain gardens that did not evolve in soils with a high

sand content can seriously affect the sustainability of plants used in the rain garden. Consequently, plant selection for sand-based rain gardens may require the use of non-native plants more suited to growing in soils with a high sand content.

The two dilemmas presented by sand-based rain gardens can be solved by using native soils rather than sand beneath the gardens. However, both the short-term and long-term success of native soil rain gardens depends upon designers having a thorough understanding of how the biological properties of the soil can work to enhance water drainage. This is presented later in this chapter.



Figure 23: Plants Native to Sandy Soils

Soil pH

What is pH and why is it important to growing healthy plants? The term "pH" stands for "**Potential Hydrogen**." Water molecules occasionally break apart to release one hydrogen atom (H^+), which is a cation, and one hydroxyl molecule (OH^-), which is an anion.

This is called the **self-ionization of water** and the result is illustrated in Figure 24. The pH scale is a measure of the number of H^+ ions in the soil; the higher the number of H^+ ions, the higher the **acidity** of the soil. As the number of number of H^+ ions in the soil decreases, the soil becomes less acid; it becomes more **alkaline** (also called "**basic**").

Soil pH drives soil chemistry. Figure 26 shows why knowing the soil's pH is important to the success of growing healthy plants. The graph shows the

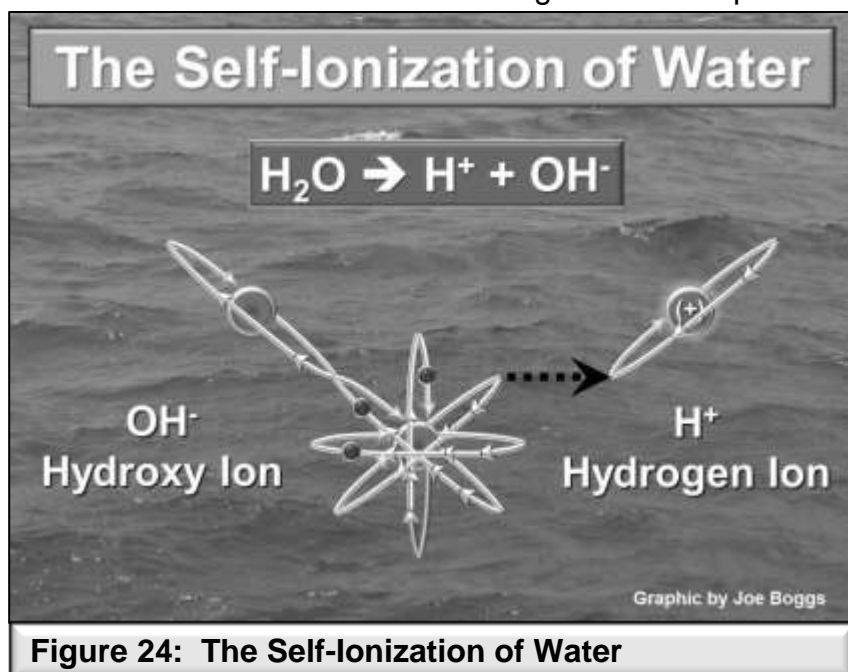


Figure 24: The Self-Ionization of Water

availability of nutrients to plants, illustrated by the width of the bands, relative to soil pH. The wider the bands, the more available the nutrient are to plants; the narrower the band the less available the nutrient are to plants. Where the bands are narrow, the nutrients may be in the soil in concentrations sufficient to support health plants; however, the H^+ or OH^- ions are "locking up" the nutrients by causing them to bond with other chemicals in the soil to create water insoluble molecules. Thus, the nutrients cannot be carried by water into plant roots.

The self-ionization of water doesn't happen very often; however, it could be argued that it is the most important chemical reaction that occurs in nature because without it, there would be little to no chemical activity in the soil.

Soil pH and Lime

The soil's acidity is based on the total number of H^+ ions in the soil; the higher the number of H^+ ions the more acidic the soil. So, raising soil pH can be accomplished by removing H^+ ions from the soil.

Lime raises the pH of soil through a chemical reaction that is called the "**lime reaction**". It causes the soil pH to move from an acid condition (below pH 7.0) to and alkaline (basic) condition (above pH 7.0). The chemical name for lime is Calcium Carbonate, and the chemical formula is $CaCO_3$. The chemical formula means that each lime molecule has 1 atom of calcium (Ca), 1 atom of carbon (C), and 3 atoms of oxygen (O).

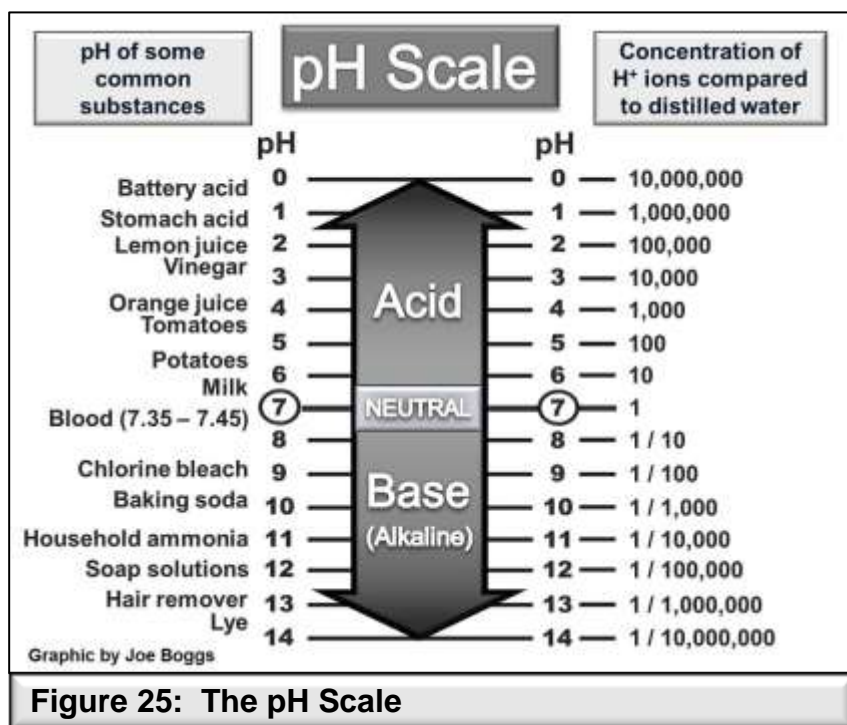


Figure 25: The pH Scale

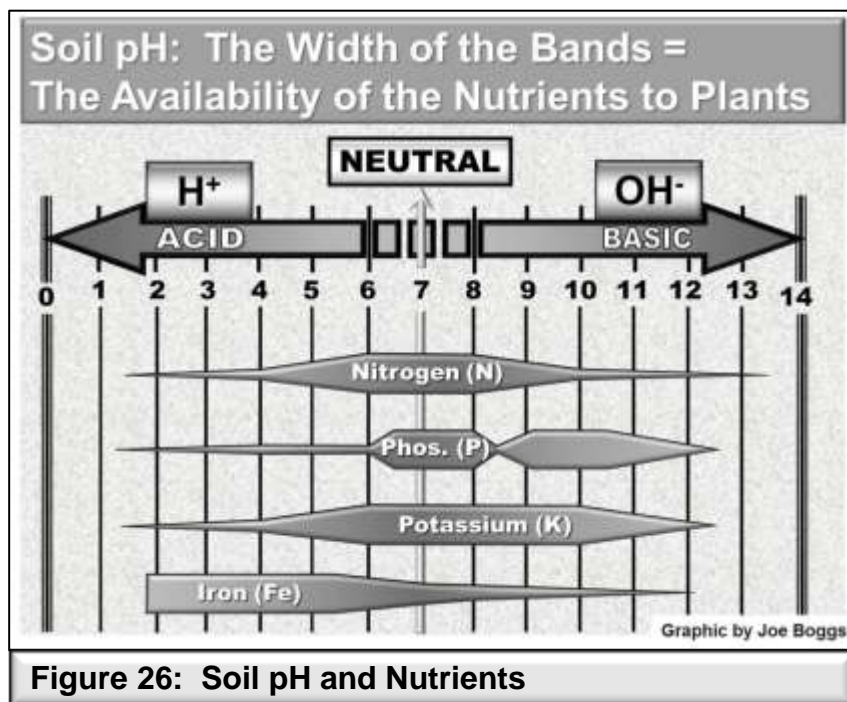
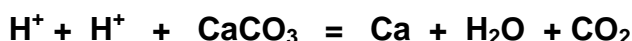


Figure 26: Soil pH and Nutrients

Here are the steps in **lime reaction** which causes soil pH to rise:

1. Each lime molecule (CaCO_3) reacts with two H^+ ions in the soil.
2. The lime molecule splits apart, and the two H^+ ions bond with one of the oxygen atoms to form water (H_2O). The soil pH rises. The water simply remains in the soil.
3. The carbon (C) atom that was once held within the chemical bonds of the lime molecule now bonds with the two remaining oxygen (O_2) to form carbon dioxide (CO_2). The carbon dioxide is a gas, so it leaves the soil and rises into the air.

The chemical equation for the "**lime reaction**" is given below. Note that the H^+ ions are floating in the soil solution; however, the chemical equation demonstrates that each calcium carbonate molecule only reacts with two H^+ ions:



Soil "Reserve Acidity" and the Buffering Capacity

Soil pH is driven by the H^+ ions that are freely floating around in the "**soil solution**." The H^+ ions that are "locked-up" by being attached to soil particles, particularly clay particles with their high CEC, does not immediately affect the soil pH; they are held in reserve. The two locations of the H^+ ions are illustrated in Figure 27. Lime first reacts with the H^+ ions that are freely floating around in the soil solution. The soil pH rises as the freely floating H^+ ions are removed by the lime reaction. However, if lime remains in the soil after all the free floating H^+ ions are removed; the H^+ ions attached to the clay particles will detach from the particles. They disembark from the CEC bus! The ions will move into the soil solution causing the soil to become more acidic; the pH will drop. In other words, the H^+ ions are held in reserve until all the freely floating H^+ ions are removed. The H^+ ions attached to the clay particles represent the "**reserve acidity**" of the soil.

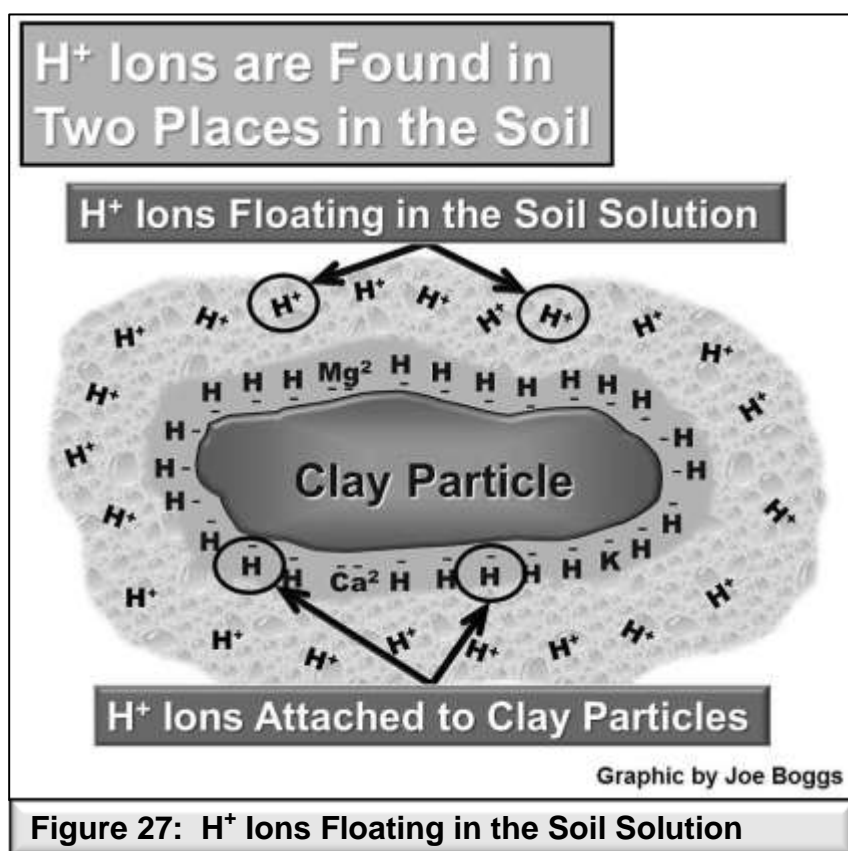
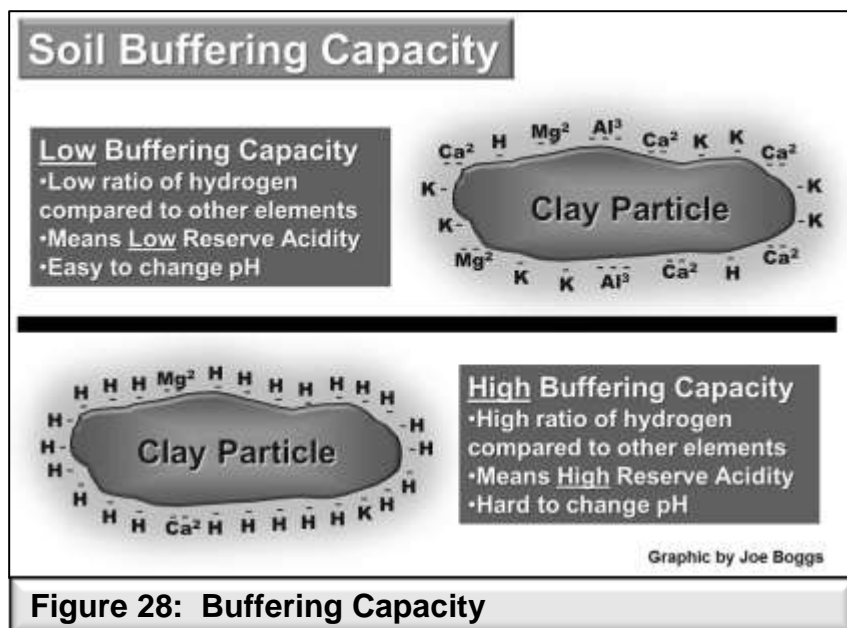


Figure 27: H^+ Ions Floating in the Soil Solution

A "**buffer**" keeps the pH the same; it preserves the "status quo." A soil with a high "**buffering capacity**" is more resistant to changes to the soil's pH (Figure 28). The greater the buffering capacity, the more difficult it is to change the pH. Thus, a soil with high reserve acidity will also have a high buffering capacity. Remember that once all the lime molecules are used up by the lime reaction, H^+ ions will stop detaching from the clay particles and moving into the soil solution to cause the pH to drop. Soils with a high buffering capacity are actually preferred over soils with a low buffering capacity. A high buffering capacity means that once the pH is changed by adding lime, the pH will tend to remain constant.



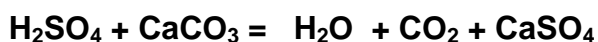
Soil pH and Sulfur

Sulfur is a basic chemical element with the chemical symbol "S." It is called a "**soil acidifier**" because it raises pH by removing calcium carbonate ($CaCO_3$) from the soil, whether the calcium carbonate came from limestone or calcite. Sulfur comes in various forms. It may be applied in the "**elemental form**" as a powder or as a pellet (pelletized sulfur) or it may be applied as part of a molecule such as iron sulfate ($FeSO_4$) which is also known as ferrous sulfate. However, the elemental form of sulfur is almost twice as effective in lowering pH because the only element being applied is sulfur.

The "**sulfur reaction**" is much more complicated compared to the lime reaction because the first step usually involves microorganisms. Here are the steps for the sulfur reaction:

1. Microorganisms take-in the sulfur and convert it to sulfuric acid (H_2SO_4).
2. The sulfuric acid reacts with the calcium carbonate molecule to break apart the molecule.
3. The reaction produces a molecule of water (H_2O), one molecule of carbon dioxide (CO_2), and one molecule of gypsum ($CaSO_4$). Note that this reaction demonstrates that gypsum is "non-reactive" in the soil; it will neither raise nor lower pH which is one reason it is a good source of calcium (Ca) compared to lime ($CaCO_3$) which raises pH.
4. The sulfur reaction takes calcium carbonate out of the "soil solution" which means it is no longer available to support the "lime reaction." In other words, pH will fall; the soil becomes more acidic.

The chemical equation for the "**sulfur reaction**" is given below. Note that the role of microorganisms is not included since they are a biological component to the process, not a chemical molecule.



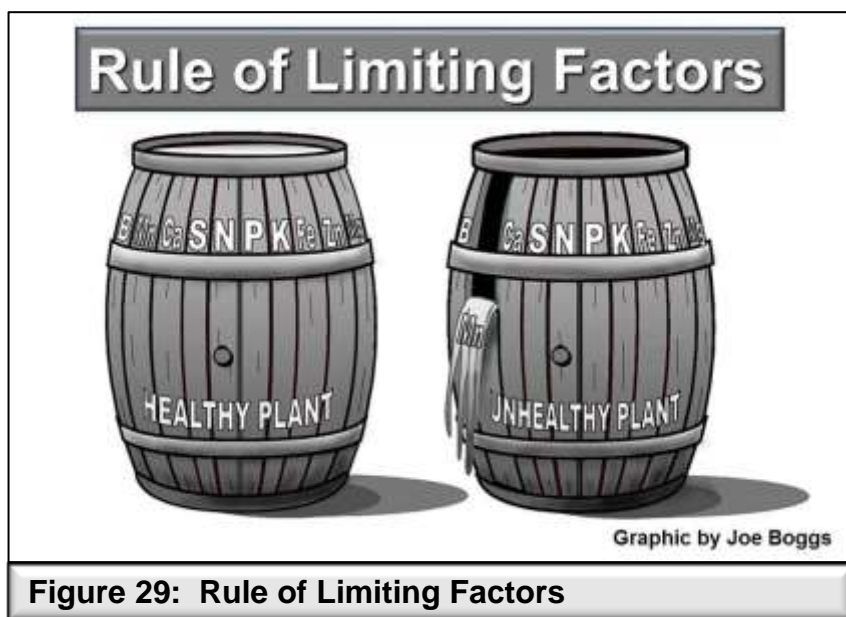
The sulfur reaction demonstrates two reasons it is much more difficult to lower soil pH compared to raising the pH with lime. First, the sulfur reaction relies on microorganisms which mean soils with little biological activity will have fewer microorganisms to support the reaction. Second, sulfur only indirectly affects pH by removing calcium carbonate from the soil; the reaction doesn't actually add H^+ ions to the soil.

Finally, the main reason sulfur is much less effective in lowering soil pH compared to how effective lime is in raising pH has to do with quantity. Just imagine how much sulfur would be needed to lower pH in topsoil that is resting on limestone bedrock that is hundreds, sometimes thousands, of feet thick; it's like shoveling sand against the tide!

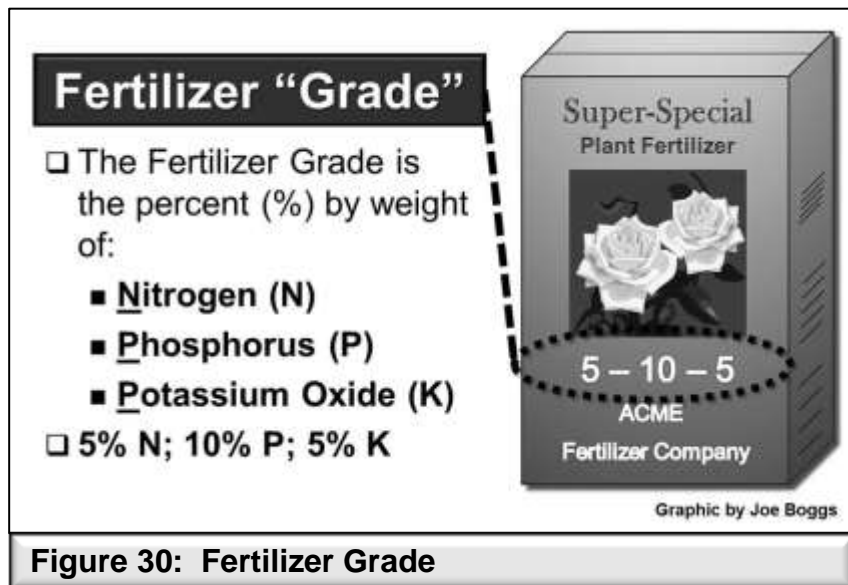
Fertilizer

The terms "macronutrient," and "micronutrient" are sometimes misunderstood. The "macro" and "micro" designation is based on the quantity of the nutrient used by plant, not on the relative importance of the nutrient; it is quantity, not quality.

The "**Rule of Limiting Factors**" (Figure 29) is used to illustrate the equal importance of all plant nutrients to overall plant health. The total volume of the two barrels represents plant health. The relative quantity of plant nutrients are represented by the length of the barrel staves. The staves of the barrel on the left are all equal in length allowing plant health to be completely full. The staves on the right has one that is shorter than the others (Mn = manganese). This short stave does not allow "plant health" to totally fill the barrel. Mn is the limiting factor in plant health!



All fertilizer products have three bold numbers, usually separated by dashes, which are displayed on the label; the three numbers are called the **fertilizer grade** (Figure 30). The numbers represent the percentages by weight of three macronutrients in the product. The first number is the percentage by weight of nitrogen (N), the second number is the percentage of phosphorus (P), and the third number is the percentage of potassium (K).



Understanding the information represented by the fertilizer grade is very important to being able to perform calculations to determine how much of the product should be applied to satisfy a fertilizer recommendation. It is also important in selecting the least costly product to meet the requirements of a fertilizer recommendation.

Fertilizer Calculation Example

Fertilizer calculations for nitrogen, phosphorus, and potassium are performed using exactly the same math equations. The following example focuses on a potassium recommendation.

Example: A soil testing laboratory fertilizer recommendation calls for 1/2 lb. of potassium to be applied per 1000 sq.ft. in order to correct a deficiency of potassium in the soil (a nutrient deficiency). You have a fertilizer product with a grade of 10 – 0 – 5. How much of this product would you need to apply to satisfy the potassium recommendation of 1/2 lb. per 1000 sq.ft.?

Steps in the Fertilizer Calculation:

1. Convert the percentage of potassium in the fertilizer to its decimal form: 5% = 0.05
2. Convert the 1/2 lb. recommendation to its decimal form: 1/2 lb. = 0.5 lb.
3. Put the numbers in the "Fertilizer Calculations Math Model" and do the math.

NOTE: Phosphorus pentoxide (P₂O₅) and dipotassium oxide (K₂O) are traditionally used in the fertilizer grade to express the amount of P and K in a fertilizer. This can cause some confusion since these compounds do not actually exist in fertilizers and their percentages do not represent the exact amount of actual P and K in the product. Fortunately, this old chemical convention can almost be ignored since fertilizer recommendations such as those from soil test laboratories are now almost always given as pounds of P₂O₅, or pounds of K₂O per acre, or 1000 sq. ft., even though you are actually applying another form of P and K. So, the simple math equations presented above will provide an accurate

result for calculating the amount of a fertilizer product that should be applied to satisfy a soil testing laboratory recommendation for either P or K.

However, should a fertilizer recommendation specify that the amounts are based on actual phosphorus or actual potassium, use the following formulas:

For phosphorus (P): $\% P_2O_5 \times 0.44 = \% \text{ actual phosphorus in the product}$

For potassium (K): $\% K_2O \times 0.83 = \% \text{ actual phosphorus in the product}$

Building Better Soil: Soil Structure

How Soil is Put Together

Once again, it is important to remember that the three properties of the soil (physical, chemical, and biological) interact to influence the ability of soils to support healthy plants. Understanding how these properties interact and how we can affect the interactions in a positive or negative way is key to understanding how we can both cause damage to soils or repair damaged soils.

For example, we have already discussed how soil texture affects the nutrient holding capacity (CEC) of the soil and the water holding capacity of soil. Both demonstrate how texture, which is a physical property, interacts with chemical properties of the soils.

However, in terms of how the soil is put together, soil texture is like the basic construction materials used to build a house. Sand, silt, and clay is like the nails, lumber, and cement that are eventually put together to form a recognizable structure; a ranch style home, or a split-level, or a two-story colonial. A pile of sand, silt, and clay is no more recognizable or functional as a soil as a pile of construction materials is recognizable or functional as a home.

Soil consistency describes the general organization of the soil where the soil is placed in one of the following descriptive categories:

- Loose
- Friable
- Firm
- Extremely Firm

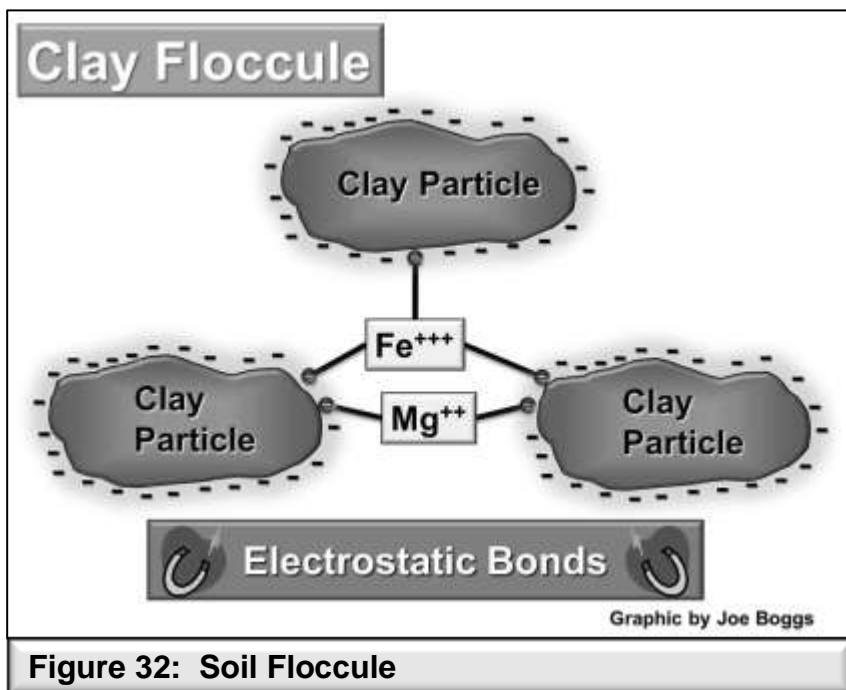
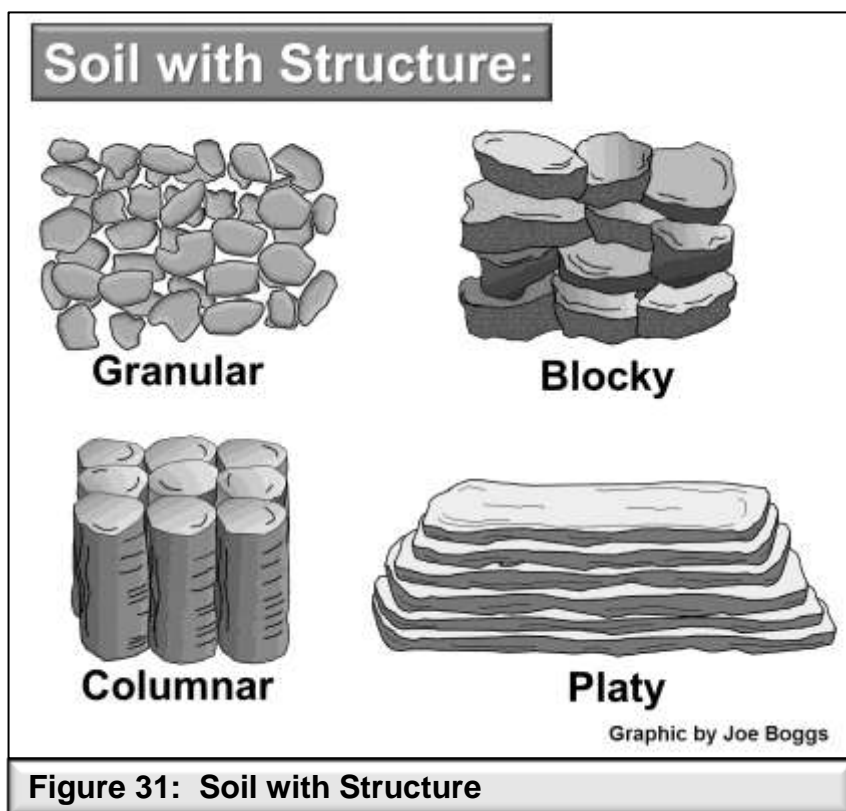
Soil consistency is often a temporary condition. For example, soil that is rototilled will become loose, or friable. However, once the rototilled soil watered, or stepped on during planting, the soil collapses and may even become firm. Soil consistency is a term that is gradually disappearing from the soil sciences literature; however, it continues to describe soils in a unique and important way. Consistency is much like looking at a house during the early stages of construction; while the design may be apparent, the final form has yet to be revealed.

Soil Structure describes how the soil is put together in its final form. The term and concept are very different from the basic building blocks represented by soil texture, or the loosely organized particles found in soil consistency. Soil structure is like the end result of home construction; it is a recognizable final form.

Clay, Soil Flocculation, and Soil Structure

As noted above, the negatively charged sites on the surface of clay particles play an important role in holding water molecules and nutrients in the soil. The negatively charged sites are also involved with initiating soil structure. Magnesium (Mg), calcium (Ca), and iron (Fe) are called **polyvalent cations** because they carry multiple positive charges. This is illustrated using multiple "plus" signs: Mg^{++} ; Ca^{++} ; and Fe^{+++} .

These polyvalent cations can reside on the surface of clay particles with Mg^{++} and Ca^{++} each occupying two sites (two "seats" on the CEC bus), and Fe^{+++} occupying three sites (three "seats"). Or, they can serve as bridges to join clay particles together with Mg^{++} and Ca^{++} joining two particles and Fe^{+++} joining together three clay



particles. The term "**flocculation**" carries different meanings depending upon the scientific discipline; however, soil scientists use flocculation to describe this process where polyvalent cations join together clay particles. Flocculation can join together many clay particles to form soil structural bodies called **floccules** (Figure 32).

Soil floccules are held together by electrostatic bonds; the same type of bonding that occurs between opposite ends of bar magnets. The weak electrostatic bonds holding the floccules together can be destroyed by a number of compounds including detergents. Indeed, this partially how soaps work to clean dirty cloths. Stripping clay particles from dirty cloths does not involve breaking much stronger chemical bonds. However, the fact that soaps and detergents can break apart clay floccules is a good reason not to irrigate landscapes and vegetable gardens using "greywater" defined as wastewater from cloths washing machines, hand washing sinks, or showers. The soaps and detergents in the water can wreak havoc on soil structure including destroying soil floccules!

Biological Properties of Soil

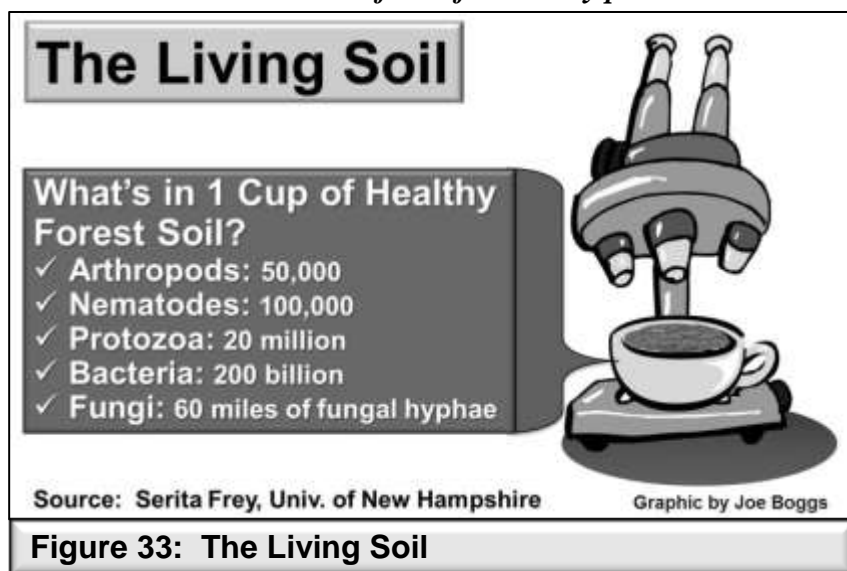
Mighty Microbes and Soil Structure

“An agricultural adage says the tiny animals that live below the surface of a healthy pasture weigh more than the cows grazing above it.” -- Carol Williams

“If a healthy soil is full of death, it is also full of life: worms, fungi, microorganisms of all kinds ... Given only the health of the soil, nothing that dies is dead for very long.” -- Wendell Berry

Healthy soils are home to a staggering number of micro- and macroorganisms. These organisms play an important role in the development of soils that support healthy plants.

Soil organisms exude sticky waste products. These sticky substances cause the soil particles to stick together, so the substances are called **microbial glue**. A small collection of soil particles that are stuck together by microbial glue is called a **soil aggregate** (= ped) and soil that contains a large collection of aggregates (peds) is called **aggregated soil**.



Note in Figure 34 that within soil aggregates there are tiny spaces called **micropores**. While water and air can exist within the micropores, their extremely small size limits their effectiveness in allowing water to move through the soil as well as their ability to hold sufficient oxygen to support healthy plant roots. They are important for nutrient retention and exchange, particularly in clay soils. Between the aggregates are large spaces called **macropores** which is illustrated in Figure 35. These large pore spaces allow water to easily move through the soil and they hold large amounts of air; the oxygen will support the growth and continued development of healthy plant roots.

Soil aggregation changes everything! The graph presented earlier in this chapter (Figure 15) showing the relationship between soil texture and soil moisture is based on non-aggregated soil. Figure 35 illustrates what happens when a clay soil is aggregated. Note that water easily moves through the soil profile by flowing through the macropores between the aggregates. However, the clay particles within the aggregates will still hold onto water allowing it to be released over time to support plant growth; the "water available to plants" labeled on the earlier graph continues to hold true in aggregated soil.

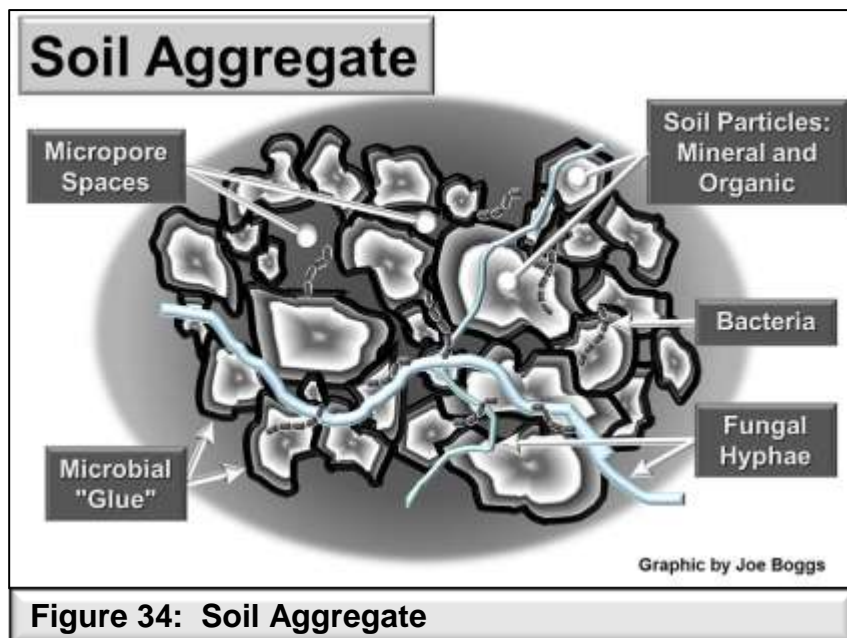


Figure 34: Soil Aggregate

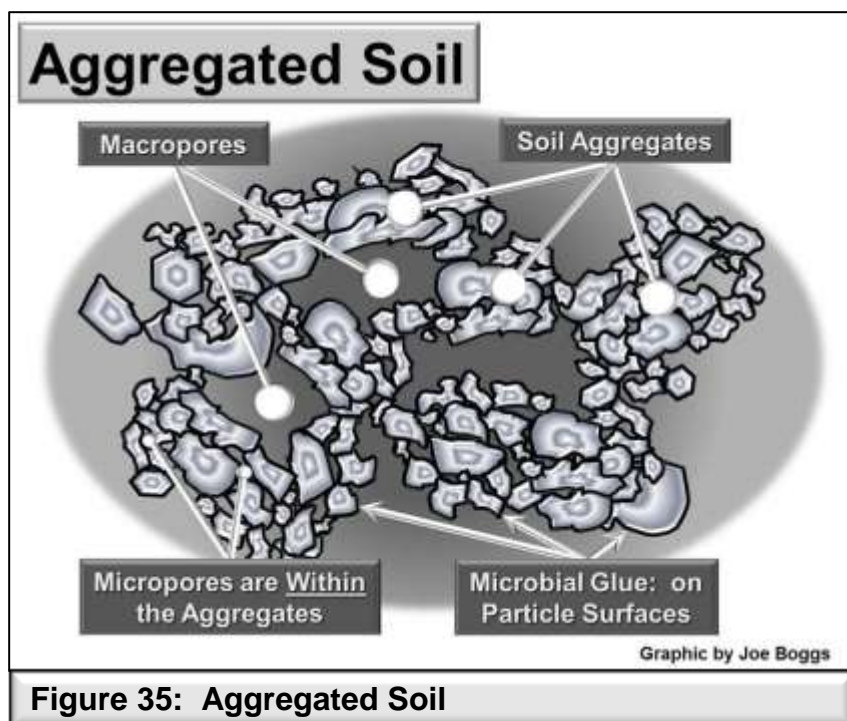


Figure 35: Aggregated Soil

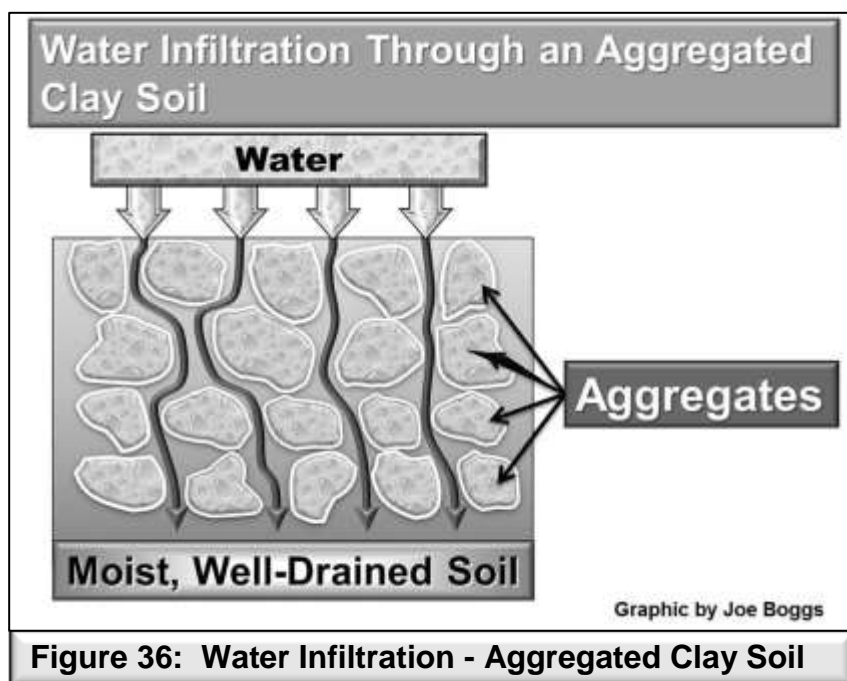
Thus, through soil aggregation, even clay soil can be made to achieve the much sought after condition of a "moist, well-drained soil." Also, the high CEC value of clay means the clay aggregates will retain more nutrients compared to silt or sand. The nutrients will not be easily washed from the soil and will be available to support plant growth and development.

Soil Structure describes how the soil is put together and aggregates endow soil with a good structure for plant growth. It takes time for soil to become aggregated, to develop good soil structure. Keep in mind that soil structure is influenced by interactions between the physical (e.g. texture), chemical (e.g. pH), and biological properties of the soil. However, the biological properties play a particularly significant role in producing good soil structure.

How can having an understanding soil structure affect **rain garden** designs? As noted above, a common rain garden design feature involves the use of sand beneath the garden; however, the heavy use of sand affects both plant selection as well as plant nutrient management. Understanding that soil aggregation directly impacts soil drainage allows rain garden designers to broaden their options to include using native soils beneath rain gardens. The key is to use organic matter in support of the microbial activity important to the creation of soil aggregation.

Organic Matters

Figure 36 illustrates the substantial payoffs achieved from adding organic matter to the soil. The benefits start with supporting enhanced biological activity of the organisms already living in the soil and with attracting new organisms which increases biological diversity. Greater diversity creates a higher likelihood that soil dwelling plant pathogenic microbes - those that are responsible for causing plant diseases - will become food for other microbes. Indeed, research conducted at the Ohio State University, Ohio Agricultural Research and Development Center (OARDC) showed a direct connection between the addition of organic matter to the soil and reduced incidences of *Phytophthora* Root Rot, so named because the disease is caused by soil borne fungi in the genus, *Phytophthora*.



Greater biological diversity also increases the chances that certain microbes found in a healthy soil ecosystem will be capable of detoxifying chemical substances that are harmful to other organisms. While it may seem counter-intuitive, one organism's poison may be another organism's food! A classic example is the rapid degradation by soil-borne bacteria of the carbamate insecticide carbofuran (e.g. Furadan). Although now banned in the U.S. for

use on food crops, carbofuran was a highly effective insecticide for controlling soil-dwelling insect pests. Unfortunately, it was also highly toxic to mammals with an oral LD50 of 8-14 mg/kg (the lower the LD50, the greater the toxicity). Farmers began reporting that the effectiveness of the insecticide was decreasing with usage, but research showed the targeted insect pests were not becoming resistant. Further research showed that soil-borne bacteria were responsible; they were using the carbofuran as food!

Note that "Aggregation Increased" is a central feature in Figure 37. As the graphic depicts, increased aggregation leads to improved pore structure which in turn leads to improved tilth and water storage. **Tilth** is a soil structural term directly related to soil aggregation; it is not a soil consistency term, so it is not equivalent to *friable*. The two terms are sometimes used interchangeably which is inaccurate. While rototilling will make soil more friable, the grinding action of the tiller will destroy soil aggregates, so tilling actually decreases soil tilth.

However, all organic matter is not equal. Figure 38 shows the Carbon : Nitrogen (C:N) ratios for several forms of organic matter. Note that a C:N ratio above 30:1 may cause problems with soil nitrogen deficiency. This is because the organic matter provides an insufficient amount of nitrogen for microorganisms to utilize all of the carbon. So, the microorganisms draw nitrogen from the soil at the expense of plants. To maximize microbial diversity, it is also important to use varied forms of organic matter to provide a varied diet for the microorganisms. Do not use one form of organic matter.

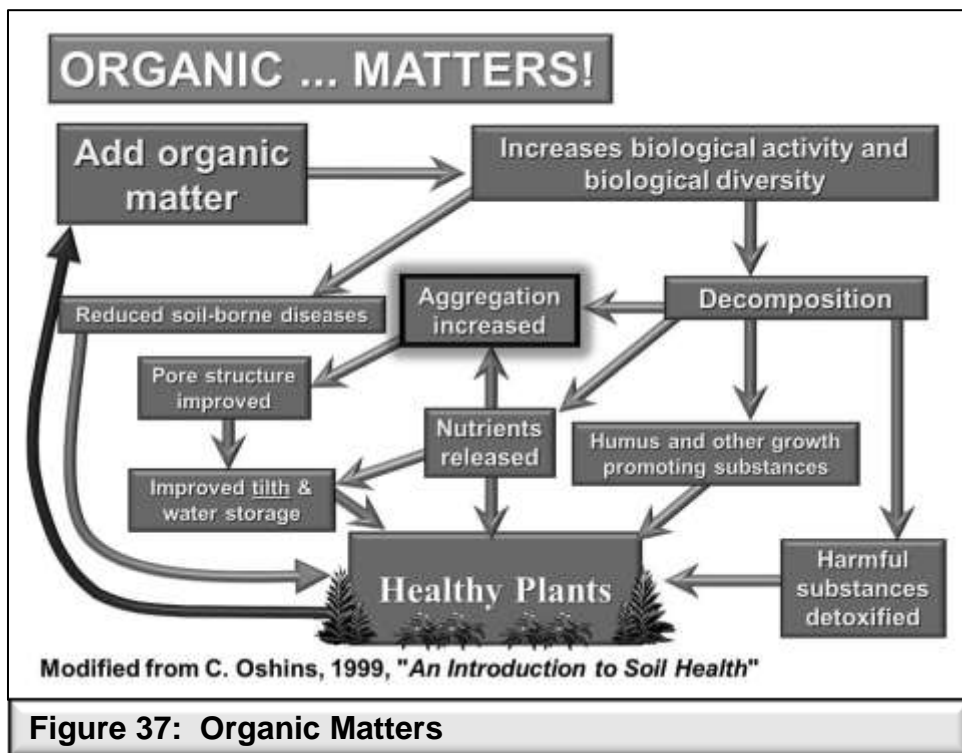


Figure 37: Organic Matters

How do you get organic matter into compacted soil? The most effective way is to use a rototiller (= rotary tiller = rotovator) such as the one shown in Figure 39. Tillers are sometimes maligned for destroying soil structure by grinding-up soil aggregates. While this is certainly a drawback with repeated usage of rototillers, a tiller is an essential tool for mixing organic matter deep into compacted soils while loosening the soil (improving soil consistency) and introducing oxygen to support aerobic decomposition of the organic matter.

Carbon : Nitrogen Ratios	
Material	C:N Ratio
Newspaper	600 : 1
Fresh Sawdust	400 : 1
Oak Leaves	90 : 1
Wheat, Oat, or Rye Straw	80 : 1
Horse Manure	50 : 1
Alfalfa Hay	20 : 1
Dairy Manure	25 : 1
Poultry Manure	18 : 1
Compost	15 : 1
Clover and Alfalfa (early)	13 : 1

A ratio above 30:1 may cause problems with soil nitrogen deficiency

Figure 38: Carbon - Nitrogen Ratios

Of course, a rototiller cannot be used in an existing perennial gardens or trees and shrubs in landscapes, but it can be used prior to establishing a new plantings. However, such an extreme measure to correct soil compaction or other soil problems should be weighed against the time and cost associated with tilling; it is essential to determine if the severity of the problem justifies the time and expenditure needed to correct the problem.



Figure 39: Rear-Tined Rototiller

A less dramatic and more long-term solution would be to provide a constant infusion of organic matter by using organic mulches. Organic mulches will not only support soil microorganisms that ultimately produce aggregated soil, but they also reduce the loss of organic matter from the soil by oxidation. Of course, mulches also reduce weed germination and establishment.

Putting It All Together:

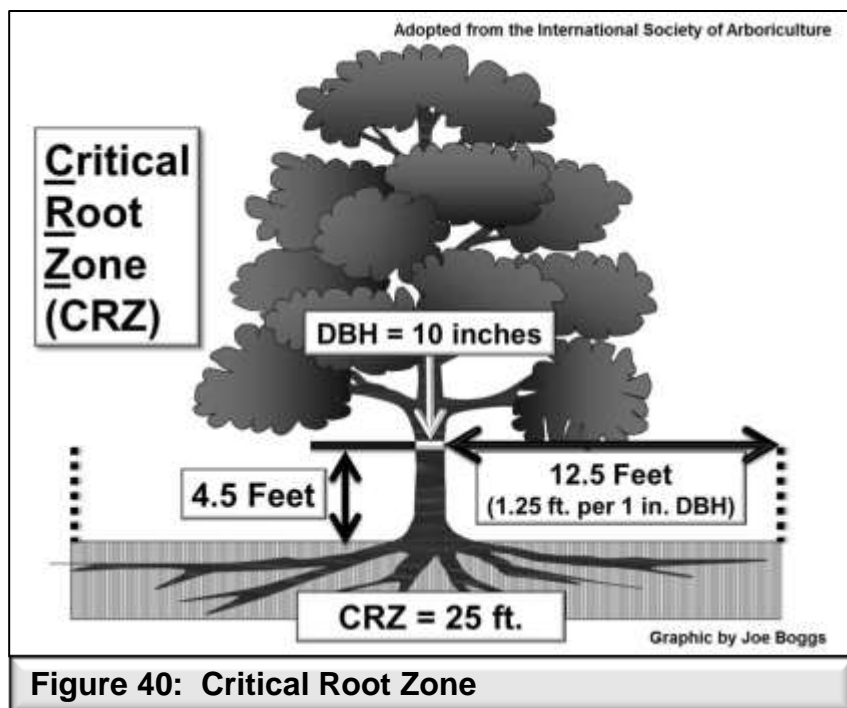
So, how do you use what you've learned to correct soil problems or to manage soils in a way that prevents soil problems? Following are some tips based on applying the information presented in this chapter:

Avoiding Soil Problems

The best way to avoid soil problems is to apply soil management practices that keep the soil healthy in the first place! You should use soil tests just like your physician uses blood tests in preventative medicine; soil tests are "blood tests for the soil." As noted above, keeping soil macro- and microorganisms healthy by supplying a continuous stream of organic matter directly affects the overall health of the soil. Rather than bagging grass clippings, a mulching mower returns grass clippings to the soil to provide an important source of organic matter to the biologicals as well as nutrients to grass plants. Mulching mowers are also useful in returning fallen leaves beneath trees to the soil. Organic mulches decay beneath trees and shrubs to provide a constant source of organic matter to soil organisms.

Next, you should limit practices that can damage the soil. This may not be easy, or always possible. However, there are certain practices that can help you to avoid damaging the soil, particularly with avoiding soil compaction. For example, working in a vegetable garden when soils are wet will substantially increase the risk of soil compaction. Using organic mulch, such as wheat straw, to protect the soil and distribute your weight will reduce soil compaction.

Tree roots can be protected during construction using a nationally recognized protective practice known as a Critical Root Zone (CRZ). A CRZ is calculated by measuring the diameter at breast height (DBH) of the tree trunk, which is measured 4.5 ft. above the ground, and multiplying each inch of DBH by 1.25 ft. For example, a tree with a 10 inch DBH would have a CRZ radius from the tree trunk of 12.5 ft. ($10 \times 1.25 = 12.5$ ft.). This area should be protected during construction. Although this method of protecting tree roots from soil compaction is less than perfect since tree root



morphology tells us the root system of a mature deciduous tree usually extends far beyond the CRZ, fencing off the calculated CRZ will still provide some relief from construction equipment causing extensive soil damage over the tree's root zone.

Diagnosing Soil Problems

Accurately identifying the soil problem will guide you in developing and applying effective corrective actions. Soil tests can play a significant role as a diagnostic tool. The tests will help you determine if there are nutrient deficiencies, or if the soil pH is interfering with nutrient availability. Most soil testing laboratories will provide recommendations on actions required to correct nutrient deficiencies.

Learning the past history of the soil can provide significant information important to diagnosing a soil problem. For example, learning that your soil was farmed continuously for many years before you purchased your property can guide you towards investigating whether or not the hard layer you've encountered several inches below the surface is a plow compaction zone, an illuviation zone, or if it is simply the subsoil horizon.

If you're helping others solve a soil problem, knowing that their home was recently built can guide you towards a diagnosis of soil compaction during construction. It may also lead you to suspect the topsoil was removed and not returned during construction. Either way, knowing the background of the site can help you ask the right questions.

Correcting Soil Problems

Some soil problems can be quickly and effectively corrected while others require more long-term strategies. Nutrient deficiencies that are disclosed by a soil test may be fixed with an application of an appropriate fertilizer. Compacted soil in a vegetable garden may be fixed by rototilling and then protecting the soil with mulch.

There is no effective long-term strategy for dealing with the problem of topsoil having been removed from the site. As noted, even with the addition of organic matter, it takes many years for subsoil to evolve into productive topsoil. The most effective fix is to return topsoil to the site. Of course, while this quickly resolves the problem, it is an expensive solution which sometimes leads to a quantity of topsoil purchased that is insufficient for truly correcting the problem.

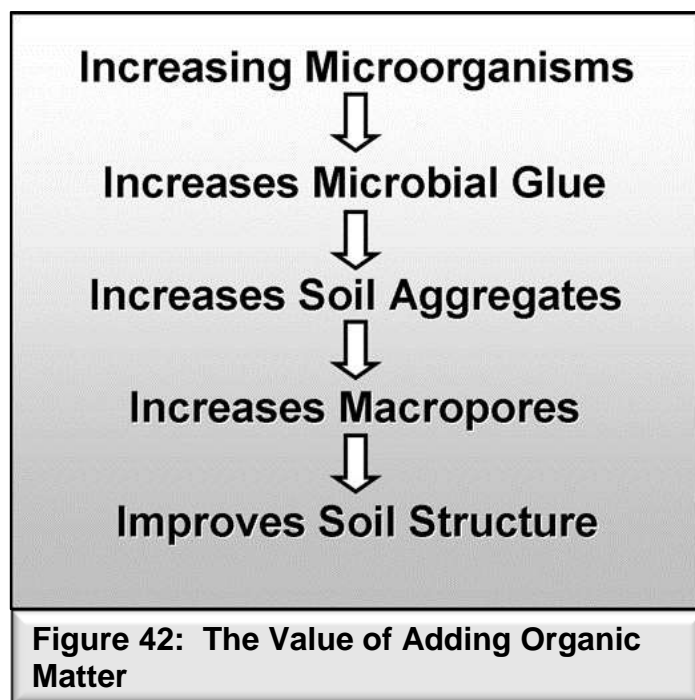
Correcting soil compaction beneath existing landscaping presents a number of



Figure 41: Air Knife®

challenges. There are some pieces of equipment that can help speed the process. For example, a hollow-tined core aerator is effective in alleviating compaction beneath turfgrass. It is important to aerate soil that is moist enough to support maximum penetration with the tines. Solid-tine aerators are not recommended since they compact the soil laterally around the holes. Arborists can use an Air Knife® or Air Spade® to alleviate soil compaction around trees and shrubs. These devices are attached to an air compressor and accelerate the air to excavate the soil without damaging tree roots. Removing soil and replacing it with soil amended with organic matter can quickly correct compaction issues.

If equipment cannot be used to correct a soil compaction problem, a successful mitigation strategy will require patience coupled with a deliberate plan. It is often said that once soil structure has been destroyed by compaction, it can never be recovered. This is only partially true. Remember that soil compaction leaves behind all of the preexisting soil horizons; the organic layer and topsoil have simply been squeezed down. While soil compaction smashes aggregates and destroys soil structure so that, good soil structure can be revived. With patience and a focus on supporting soil microorganisms that produce the microbial glue which bonds soil particles into aggregates; even heavily compacted soils can be returned to healthy, productive soils. It's a natural process, after all!



A Final Comment:

Why is soil so important? William Butler Yeats said it best:

*"All that we did, all that we said or sang
Must come from contact with the soil ..."*