Soil Chemistry

Definition of Soil

- KNIGHT (1956) defined soil as the mineral material that exists in solid or unbroken form such as boulders and gravels or finely divided particles of mineral matter such as sand, silt or clay depending upon the texture.
- Ruffin and Simonson (1968): Soil is a mixture of Earth's uppermost mantle of weathered rock and organic matter
- Buckman and Brady (1969): Soil is a dynamic natural body on the surface of the earth in which plants grow, composed of mineral and organic materials and living forms
- TRESHOW (1970) gave a more appropriate definition of soil. He defined soil as a complex physical-biological system providing support, water, nutrient and oxygen for the plants

Soil Profile

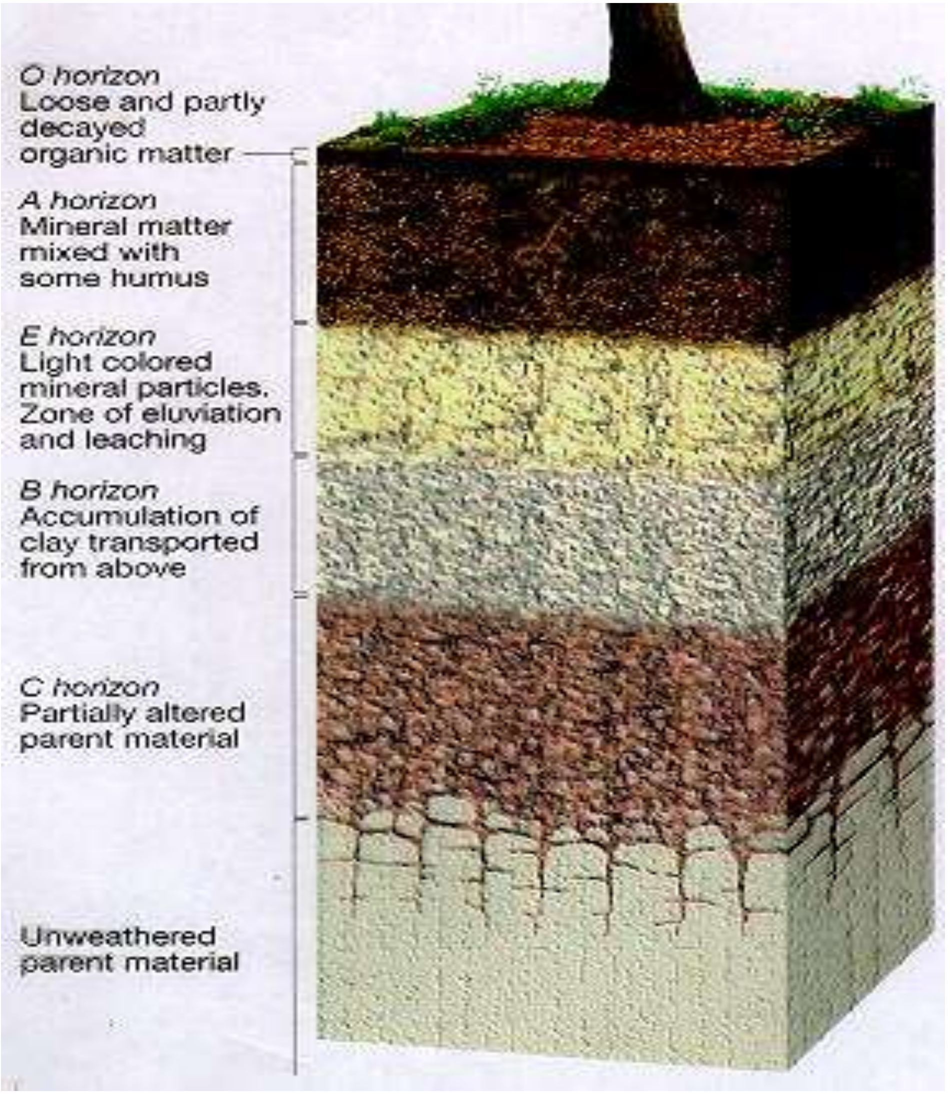
- The soil profile is an important tool in nutrient management. By examining a soil profile, we can gain valuable insight into soil fertility. As the soil weathers and/or organic matter decomposes, the profile of the soil changes.
- For instance, a highly weathered, infertile soil usually contains a light-colored layer in the subsurface soil from which nutrients have leached away. On the other hand, a highly fertile soil often has a deep surface layer that contains high amounts of organic matter.

Components of a Soil Profile

- A soil horizon refers to a distinct layer within the soil, running approximately parallel to the surface and possessing unique properties and characteristics compared to the layers above and below it.
- The soil profile represents a vertical cross-section of the soil, encompassing all its horizons. This profile extends from the surface down to the parent rock material.
- The regolith consists of all the weathered material within the soil profile and is divided into two parts: the solum and the saprolite.
- The solum comprises the uppermost horizons, which are the most weathered sections of the profile. The saprolite, on the other hand, is the less weathered layer situated just above the solid, consolidated bedrock but beneath the rest of the regolith.

Soil Profile

- There are 5 master horizons in the soil profile. Not all soil profiles contain all 5 horizons; and so, soil profiles differ from one location to another. The 5 master horizons are represented by the letters: O, A, E, B, and C.
- O: The O horizon is a surface horizon that is comprised of organic material at various stages of decomposition. It is most prominent in forested areas where there is the accumulation of debris fallen from trees.
- A: The A horizon is a surface horizon that largely consists of minerals (sand, silt, and clay) and with appreciable amounts of organic matter. This horizon is predominantly the surface layer of many soils in grasslands and agricultural lands.
- E: The E horizon is a subsurface horizon that has been heavily leached. Leaching is the process in which soluble nutrients are lost from the soil due to precipitation or irrigation. The horizon is typically light in color. It is generally found beneath the O horizon.
- B: The B horizon is a subsurface horizon that has accumulated from the layer(s) above. It is a site of deposition of certain minerals that have leached from the layer(s) above.
- C: The C horizon is a subsurface horizon. It is the least weathered horizon. Also known as the saprolite, it is unconsolidated, loose parent material.



Source:
http://courses.missouristate.edu/ejm893f/creative/glg110/Weathering.html

Characteristics of Soil

- Physical properties (mechanical behavior) of a soil greatly influence its use and behavior towards plant growth. The plant support, root penetration, drainage, aeration, retention of moisture, and plant nutrients are linked with the physical condition of the soil.
- Physical properties also influence the chemical and biological behavior of soil. The physical properties of a soil depend on the amount, size, shape, arrangement and mineral composition of its particles. These properties also depend on organic matter content and pore spaces.
- Soil Structure:Soil structure refers to the arrangement of soil particles (sand, silt, and clay) into stable units called aggregates (known to soil scientists as peds). Aggregation is important for increasing stability against erosion, for maintaining porosity and soil water movement, and for improving fertility and carbon sequestration in the soil.
- Soil Texture:The particles that make up soil are categorized into three groups by size – sand, silt, and clay. Sand particles are the largest and clay particles the smallest. Most soils are a combination of the three.
- Soil Porosity:The space between soil particles is the pore space. This pore space contains varying amounts of water and air. Soil porosity depends on soil texture and structure. Soils with lesser bulk densities have greater porosities. Good porosity is essential to adequate soil aeration, water drainage and root penetration.

- *Soil Color*
- Soil color is influenced primarily by soil mineralogy—telling us what is in a specific soil. Soils high in iron are deep orange-brown to yellowish-brown. Those soils that are high in organic matter are dark brown or black. Color can also tell us how a soil "behaves."
- *Soil Permeability*
- Soil permeability is a measure of the ease with which air and water move through the soil. A consistent and moderate supply of water, along with deep and spreading root growth are some of the benefits of good drainage or permeability. Plants need good internal soil drainage to grow.
- *Bulk Density*
- Bulk density of a soil is defined as the weight per unit volume of soil. A unit volume of soil includes both the solids and the pore space. Bulk density is important because it reflects the porosity of a soil. Loose, porous soils have lesser bulk densities than tight, compacted soil.

Chemical Properties

- Chemical properties reflect the influence between soil solution (soil water and nutrients) and exchange sites (clay particles, organic matter); plant health; the nutritional requirements of plant; and levels of soil contaminants and their availability for uptake by plants.
- *Soil pH*
- Soil pH is the foundation of essentially all soil chemistry and nutrient reaction and should be the first consideration when evaluating a soil test. Soil pH refers to the acidity or alkalinity of the soil. It is a measure of the concentration of free hydrogen ions and hydroxide ions that are in the soil. The total range of the pH scale is from 0 to 14. Soil pH is neutral when it is 7 and acid when the pH is less than 7 and alkaline when it is greater than 7. A neutral pH occurs where the hydrogen and hydroxide concentrations are equal .
- *Buffer pH*
- In addition to soil pH, many soil tests provide a reading called buffer pH (sometimes called lime index). Soil pH is a measure of hydrogen ion concentration in the soil solution, which is called active acidity—an indicator of current soil conditions. However, there are hydrogen ions, referred to a reserve acidity that are released into the soil solution to replace those neutralized by the lime.

- Electrical Conductivity:Electrical conductivity (ECe) is a measure of the total soluble salt concentration in a soil (i.e., salinity). Sodium chloride is the most common salt and others include bicarbonates, sulfates, and carbonates of calcium, potassium, and magnesium. A high ECe value corresponds with high amounts of soluble salts, and vice versa. ECe values can be expressed in micromhos/cm (μmhos/cm), millimhos/ centimeter (mmhos/cm), or decisiemens/meter (dS/m).

Soil Temperature

- Soil temperature affects seed germination and root growth, and is the result of many factors:
- Direction of slope: determines exposure to the sun. In the northern hemisphere north-facing slopes receive less sun than south-facing ones; in the southern hemisphere the opposite is true
- Depth: with increasing depth below the soil surface, the less the soil temperature changes daily and seasonally, and the more changes in soil temperature lag behind changes in air temperature.
- Color: dark-colored soils absorb more solar radiation (heat) than light soils.
- Water content: water in the soil moderates temperature; large amounts of heat are used to evaporate water, keeping soil cool on hot days, and, large amounts of heat are given off when water freezes, keeping soil warm on cold nights.
- Surface cover: covering the soil surface with a mulch slows heating and cooling both seasonally and daily, and can be used to regulate soil temperature according to the time of year and crop .

Soil Water

- Soil retains large quantities of water. An ordinary garden soil contains about 25% water by volume. The principle source of soil water is rain. After a heavy rainfall, the water is retained by soil in various forms. On the basis of water retained by_ soil, it has been classified as *gravitational water*, *capillary water*, *hygroscopic water* and *combined water.*

1. Gravitational Water

- This is the free water which due to the action of gravity moves downwards into the soil until it reaches the water-table. This water is of little direct value to the plants.

2. Capillary Water

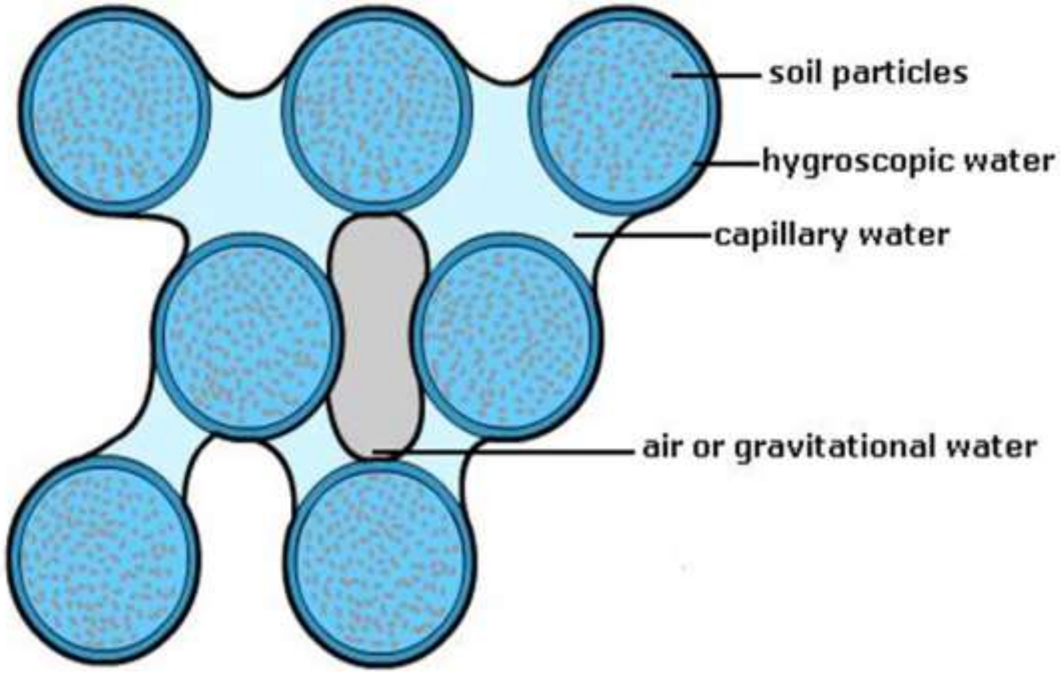
This water fills the spaces between colloidal soil particles or forms films around them. This water is held by the capillary forces around and between the particles and is of greatest importance to plant life

3. Hygroscopic Water

- The water that occurs in the form of thin film on the soil particles is termed as hygroscopic water. This water is not available to the plants.

4.Combined Water

A small portion of the soil water is chemically bound with soil materials. It is known as combined water.



Soil organic matter

- Organic matter is made up of different components that can be grouped into three major types: 1. Plant residues and living microbial biomass. 2. Active soil organic matter also referred to as detritus. 3. Stable soil organic matter, often referred to as humus.
- The living microbial biomass includes the microorganisms responsible for decomposition (breakdown) of both plant residues and active soil organic matter or detritus.
- Humus is the stable fraction of the soil organic matter that is formed from decomposed plant and animal tissue. It is the final product of decomposition.
- The first two types of organic matter contribute to soil fertility because the breakdown of these fractions results in the release of plant nutrients such as nitrogen, phosphorus, potassium, etc.
- The humus fraction has less influence on soil fertility because it is the final product of decomposition (hence the term "stable organic matter").

- Benefits of Stable Soil Organic Matter :
- There are numerous benefits to having a relatively high stable organic matter level in an agricultural soil. These benefits can be grouped into three categories:
- Physical Benefits :
- Enhances aggregate stability, improving water infiltration and soil aeration, reducing runoff.
- Improves water holding capacity. Reduces the stickiness of clay soils making them easier to till. Reduces surface crusting, facilitating seedbed preparation. C
- Chemical Benefits : Increases the soil's CEC or its ability to hold onto and supply over time essential nutrients such as calcium, magnesium and potassium.
- Improves the ability of a soil to resist pH change; this is also known as buffering capacity .
- Accelerates decomposition of soil minerals over time, making the nutrients in the minerals available for plant uptake.
- Biological Benefits : Provides food for the living organisms in the soil.
- Enhances soil microbial biodiversity and activity which can help in the suppression of diseases and pests. Enhances pore space through the actions of soil microorganisms. This helps to increase infiltration and reduce runoff.

- Soil is composed of both organic and inorganic components, each playing a crucial role in its structure, fertility, and function.
- **Organic Components**
- **Humus**: Decomposed organic matter that is rich in nutrients and improves soil structure, water retention, and fertility.
- **Living Organisms**: Includes bacteria, fungi, insects, earthworms, and other microorganisms that help decompose organic matter, fix nitrogen, and contribute to soil health.
- **Plant Residues**: Leaves, stems, roots, and other plant parts that are in various stages of decomposition.
- **Animal Remains**: Decomposed remains of animals, including bones, skin, and other organic matter.

Inorganic Components

- **Minerals**: Derived from the weathering of rocks, minerals like sand, silt, and clay make up the bulk of the soil's inorganic content.
  - **Sand**: Coarse particles that contribute to soil drainage.
  - **Silt**: Medium-sized particles that help in retaining moisture.
  - **Clay**: Fine particles that can hold water and nutrients well.
- **Water**: Occupies the spaces between soil particles, necessary for chemical reactions and plant uptake of nutrients.
- **Air**: Fills the gaps between soil particles, providing oxygen to plant roots and soil organisms.
- **Nutrients**: Essential elements like nitrogen, phosphorus, potassium, calcium, and magnesium, which are absorbed by plants for growth.
- Together, these components interact to form the complex environment that supports plant growth and sustains ecosystems.

- The main ions associated with CEC in soils are the exchangeable cations calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}) and potassium (K^{+}) (Rayment and Higginson 1992), and are generally referred to as the base cations.
- In most cases, summing the analysed base cations gives an adequate measure of CEC (‘CEC by bases’).
- However, as soils become more acidic these cations are replaced by H^{+}, Al^{3+} and Mn^{2+}, and common methods will produce CEC values much higher than what occurs in the field (McKenzie *et al.* 2004).
- This ‘exchange acidity’ needs to be included when summing the base cations and this measurement is referred to as effective CEC (ECEC).

Soil Macro nutrients

- Sixteen plant food nutrients are essential for proper crop development. Each is equally important to the plant, yet each is required in vastly different amounts. These differences have led to the grouping of these essential elements into three categories; primary (macro) nutrients, secondary nutrients, and micronutrients.
- PRIMARY (MACRO) NUTRIENTS
- Primary (macro) nutrients are nitrogen, phosphorus, and potassium. They are the most frequently required in a crop fertilization program. Also, they are need in the greatest total quantity by plants as fertilizer.
- NITROGEN
- · Necessary for formation of amino acids, the building blocks of protein
- · Essential for plant cell division, vital for plant growth
- · Directly involved in photosynthesis
- · Necessary component of vitamins
- · Aids in production and use of carbohydrates
- · Affects energy reactions in the plant

PHOSPHORUS

- Involved in photosynthesis, respiration, energy storage and transfer, cell division, and enlargement

· Promotes early root formation and growth

· Improves quality of fruits, vegetables, and grains

· Vital to seed formation

· Helps plants survive harsh winter conditions

· Increases water-use efficiency

· Hastens maturity

POTASSIUM

Carbohydrate metabolism and the break down and translocation of starches

· Increases photosynthesis

· Increases water-use efficiency · Essential to protein synthesis

· Important in fruit formation · Activates enzymes and controls their reaction rates

· Improves quality of seeds and fruit · Improves winter hardiness

· Increases disease resistance

Micro nutrients

- MICRONUTRIENTS
- The micronutrients are boron, chlorine, cooper, iron, manganese, molybdenum, and zinc. These plant food elements are used in very small amounts, but they are just as important to plant development and profitable crop production as the major nutrients. Especially, they work "behind the scene" as activators of many plant functions.
- BORON
- Essential of germination of pollon grains and growth of pollen tubes
- Essential for seed and cell wall formation
- Promotes maturity
- Necessary for sugar translocation
- Affects nitrogen and carbohydrate
- CHLORINE
- Not much information about its functions
- Interferes with P uptake
- Enhances maturity of small grains on some soils

- COPPER
- · Catalyzes several plant processes
- · Major function in photosynthesis
- · Major function in reproductive stages
- · Indirect role in chlorophyll production
- · Increases sugar content
- · Intensifies color
- · Improves flavor of fruits and vegetables
- IRON
- · Promotes formation of chlorophyll
- · Acts as an oxygen carrier
- · Reactions involving cell division and growth
- MANGANESE
- · Functions as a part of certain enzyme systems
- · Aids in chlorophyll synthesis
- · Increases the availability of P and CA

- MOLYBDENUM
- Required to form the enzyme "nitrate reductas" which reduces nitrates to ammonium in plant
- Aids in the formation of legume nodules
- Needed to convert inorganic phosphates to organic forms in the plant
- ZINC
- Aids plant growth hormones and enzyme system
- Necessary for chlorophyll production
- Necessary for carbohydrate formation
- Necessary for starch formation
- Aids in seed formation
- The secondary nutrients are calcium, magnesium, and sulphur. For most crops, these three are needed in lesser amounts that the primary nutrients.

Ion Exchange Capacity

- Soil Ion Exchange Capacity (often referred to as Cation Exchange Capacity or CEC) is a measure of the soil's ability to hold and exchange positively charged ions (cations). It is a critical property of soil that influences its fertility, nutrient availability, and ability to retain essential nutrients for plants.
- **Key Concepts of Ion Exchange Capacity**
- **Cations**: Positively charged ions, such as calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), sodium (Na^+), and hydrogen (H^+), which are essential nutrients for plants.
- **Soil Particles**: Soil particles, particularly clay and organic matter (humus), have negative charges on their surfaces. These negative charges attract and hold onto cations.

Cation Exchange Capacity (CEC)

Definition: CEC is the total capacity of soil to hold exchangeable cations. It is expressed in milliequivalents per 100 grams of soil (meq/100g).Importance: Soils with higher CEC can hold more nutrients, making them available for plant uptake. Conversely, soils with low CEC may not retain nutrients well, leading to leaching and nutrient deficiencies.

Factors Affecting CEC: Soil Texture: Clay soils generally have higher CEC because clay particles are small and have more surface area to hold cations. Sandy soils have low CEC.

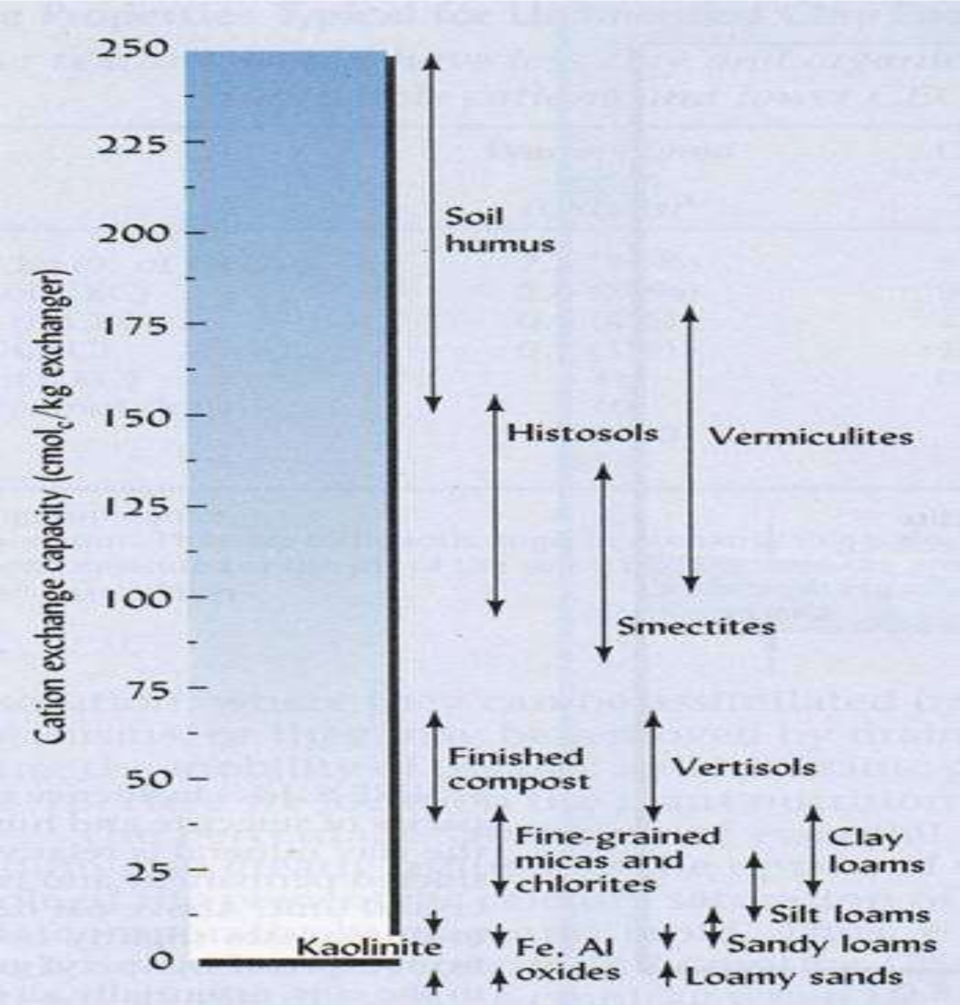
Organic Matter: Soils rich in organic matter (humus) have higher CEC due to the numerous negative charges associated with organic molecules.

pH: Soil pH affects the CEC. In acidic soils, hydrogen ions (H^+) can occupy cation exchange sites, reducing the soil's ability to hold other nutrients.

- **Practical Implications of CEC**
- **Fertilization**: Knowing the CEC of soil helps in determining the appropriate amount and type of fertilizer. Soils with low CEC may require more frequent fertilization in smaller amounts, as they do not retain nutrients well.
- **Soil Amendments**: Adding organic matter or clay to soil can improve CEC, enhancing the soil's fertility and nutrient-holding capacity.
- **Soil Health**: Monitoring and managing CEC is vital for maintaining soil health and ensuring sustainable agricultural practices.

CEC values of various soil type, media, and minerals. Soils which have high amounts of organic matter and moderately weathered clays tend to have high CECs. As soils become highly weathered, the CEC of the soil decreases. Sandy soils, too, generally have lower CEC values. This is due to the lesser surface of sandy particles in comparison with clay minerals, which decreases the ability of sand particles to hold and retain nutrients.

Source: Brady and Weil. 2002. Elements of the Nature and Properties of Soil. Prentice Hall, New Jersey.



Anion Exchange Capacity

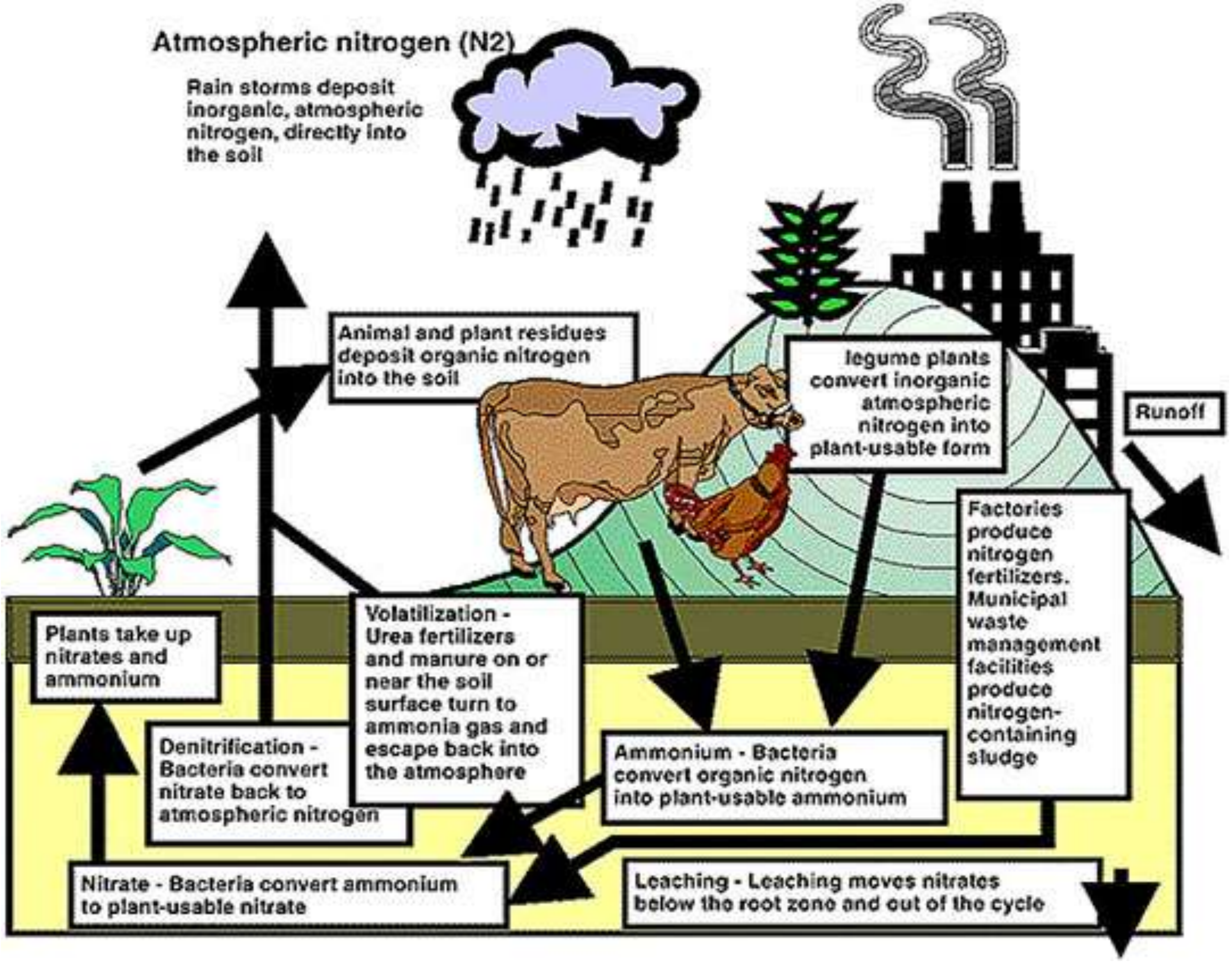
- **Anion Exchange Capacity (AEC):** In the tropics, many highly weathered soils can have an anion exchange capacity. This means that the soil will attract and retain anions, rather than cations.
- In contrast to cations, anions are negatively charged. The anions held and retained by soil particles include phosphate, sulfate, nitrate and chlorine (in order of decreasing strength). In comparison to soils with cation exchange capacity, soils with an anion capacity have net positive charge.
- Soils that have an anion exchange capacity typically contain weathered kaolin minerals, iron and aluminum oxides, and amorphous materials. Anion exchange capacity is dependent upon the pH of the soil and increases as the pH of the soil decreases.

Biological Properties

- An incredible diversity of organism’s make-up the soil food web ranging in size from the tiniest one-celled bacteria, algae, fungi, and protozoa, to the more complex nematodes and micro-arthropods, to the visible earthworms, insects, and small vertebrates. While some soil fauna can cause diseases in plants, the vast majority of soil fauna and flora are critical to soil quality. They affect soil structure and, therefore, soil erosion and water availability. They can protect plants from pests and diseases and are central to decomposition and nutrient cycling. The maintenance of this living aspect of the soil is essential to the maintenance of a healthy field.
- Bacteria:Bacteria are the most numerous type of soil organism: every gram of soil contains at least a million of these tiny one-celled organisms. One of the major benefits bacteria provide for plants is in making nutrients available to them.
- Fungi:Fungi come in many different species, sizes, and shapes in soil. Some species appear as threadlike colonies, while others are one-celled yeasts. Many fungi aid plants by breaking down organic matter or by releasing nutrients from soil minerals. Fungi are generally quick to colonize larger pieces of organic matter and begin the decomposition process. Arbuscular mycorrhizal (my-cor-ry¢-zal) fungi are beneficial soil organisms that contribute to many aspects of soil health. Mycorrhizal fungi form a symbiotic association with plant roots. Symbiosis is a close association between different species. Mycorrhizal fungi are especially effective in helping plants acquire phosphorus, a nutrient that is highly immobile in the soil.

- *Nematodes:*Nematodes are abundant in most soils, and only a few species are harmful to plants. The harmless species eat decaying plant litter, bacteria, fungi, algae, protozoa, and other nematodes. Like other soil predators, nematodes speed the rate of nutrient cycling.
- *Arthropods:*Arthropods are species of soil organisms that can be seen by the naked eye. Among them are sowbugs, millipedes, centipedes, slugs, snails, and springtails. These are the primary decomposers. Their role is to eat and shred the large particles of plant and animal residues. Some bury residue, bringing it into contact with other soil organisms that further decompose it.
- *Earthworms:*Earthworm burrows enhance water infiltration and soil aeration. Fields that are “tilled” by earthworm tunneling can absorb water at a rate four to 10 times that of vineyards lacking worm tunnels. This reduces water runoff, recharges groundwater, and helps store more soil water for dry periods.

Nitrogen cycle



- Nitrogen is important to all life. Nitrogen in the atmosphere or in the soil can go through many complex chemical and biological changes, be combined into living and non-living material, and return back to the soil or air in a continuing cycle. This is called the nitrogen cycle.
- Nitrogen is a critical nutrient in the survival and success of all organisms . Around 78% of the Earth's atmosphere is made up of nitrogen. This nitrogen in the atmosphere occurs as dinitrogen gas (N_2) and is unable to be used directly by living organisms such as plants which can limit nitrogen availability ecosystems .
- The nitrogen cycle is a key component in many ecosystem processes such as decomposition and primary production. Nitrogen availability can alter the rate of these processes. Nitrogen has several forms including dinitrogen gas (N_2), nitrogen oxide (NO), nitrogen dioxide (NO_2), ammonia (NH_3), ammonium (NH_4^+), and ammonium nitrate (NH_4NO_3).

- Through a series of processes nitrogen can be converted by microbial activities through fixation, assimilation, ammonification, nitrification, and denitrification. These processes make up the nitrogen cycle and play an important role for all living organisms on Earth.
- **Nitrogen fixation:**
- Nitrogen fixation is the process by which nitrogen gas (N2), is transformed into ammonium (NH4-), a form of nitrogen that can be used by plants. Through this process nitrogen is moved from the atmosphere into the soil where plants can absorb it through their root system. A small percentage of fixation can occur via abiotic activities such as lightening.
- A majority of nitrogen fixation occurs naturally in soils by bacteria that have a symbiotic relationship with the plants . In exchange for energy from photosynthesis the bacteria will fix nitrogen into a usable form for the plant by using the enzyme nitrogenase. Nitrogen fixation by bacteria can also produce forms of nitrogen that can be utilized by various organisms. This fixation process requires a great deal of energy and therefore uses a lot of ATP.

- A common symbiont, nitrogen fixing bacteria , fix the most nitrogen. The two most common of these symbiotic bacteria are *Rhizobium* and *Bradyrhizobium*. Both of these are able to invade the roots of legume plants. These bacteria provide plants with usable nitrogen to assist with protein production and the plants provide energy in the form of carbon for the symbiont bacteria.
- This process is beneficial to agriculture as leguminous plants can assist with returning nitrogen into the soil to promote plant growth.
- Many farmers will use a crop rotation system where leguminous plants, such as alfalfa, will be grown and then plowed back into the soil to increase nitrogen availability for crops the following year.

- **Assimilation:**
- Assimilation of inorganic nitrogen is the process by which organic nitrogen compounds form from inorganic nitrogen compounds in an ecosystem. Plants use these ions to make proteins and nucleic acids [6]. Nitrogen assimilation requires ATP and reduced ferredoxin from photosynthesizing cells in plants .
- The assimilation process occurs when nitrates enter a cell and are reduced to ammonia.
- This ammonia is then incorporated into organic compounds through the glutamine synthetase- glutamate synthase pathway (see figure 3). Through this pathway ammonia and glutamate are catalyzed by glutamine synthase into glutamine.
- Glutamine is then catalyzed by glutamate synthase into two glutamate molecules. One of these molecules will go back into the pathway, the other goes into transamination reactions to form other amino acids.

- **Ammonification/ Mineralization:**
- Soil nitrogen can be derived from dead organic materials. Ammonification or mineralization is the process where bacteria incorporate nitrogen into amino acids and release the excess nitrogen as ammonium ions (NH_4^+) into the soil. These ammonium ions are then readily available for uptake by plants for protein synthesis and microorganisms that require it for growth .
- **Nitrification:**
- Nitrification is a two-part oxidation process of ammonium ions into nitrates and nitrites moderated by many microbial communities in the ecosystem . This process provides extra available nitrogen for plants to take in via their roots. Through the process of nitrification, ammonium, produced by ammonification, found in soils is transformed into nitrites (NO_2^-) and nitrates (NO_3^-). Nitrates are able to be used by plants and plant consuming animals and are formed by ammonia-oxidizing bacteria. Nitrites are not readily available to plants and animal but can be converted to nitrates by bacteria. These nitrite-oxidizing bacteria, nitrobacteria, receive energy in exchange for this process . Nitrate is the form most living plants use to absorb nitrogen.
- **Denitrification:**
- Denitrification follows the process of nitrification and is where nitrates are returned to the atmosphere as nitrogen gas by denitrifying bacteria in soils . Denitrification generally occurs in anoxic environments with exhausted oxygen levels. This process can lead to a loss in soil nitrogen content which needs to be replaced. Denitrification can also occur during the process of harvesting crops,soil erosion, burning, and leaching.

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