Appendix A

Basic Soil Science and Soil Fertility

Introduction

Understanding the nutritional needs of plants can be quite complex, given the dynamic nature of plant nutrients in the soil. Nutrients can exist in organic or inorganic forms and in various phases. They can exist in solution, on mineral surfaces, or be retained in the structural framework of soils. Environmental conditions affect nutrients' transformations and movement in the soil, which determines their availability for plant uptake. In managed systems, understanding those transformations is essential for maintaining nutrient balances to properly supply a plant's nutritional requirements with minimal effect on the environment.

Soil Formation and Basic Morphology

Soil is the layer of unconsolidated material on the immediate surface of the earth that is capable of supporting plant life. Most soils contain four basic components: mineral particles, water, air, and organic matter. Organic matter can be further subdivided into roots, living organisms, and humus (a dark colored, semi-soluble organic substance formed from decomposition of other soil organic matter). A soil in good condition for plant growth will have a volume composition of approximately 50 percent solid material and 50 percent pore space. Under ideal moisture conditions for plants, the soil pore space would also consist of about half air and half water by volume (Figure A-1).

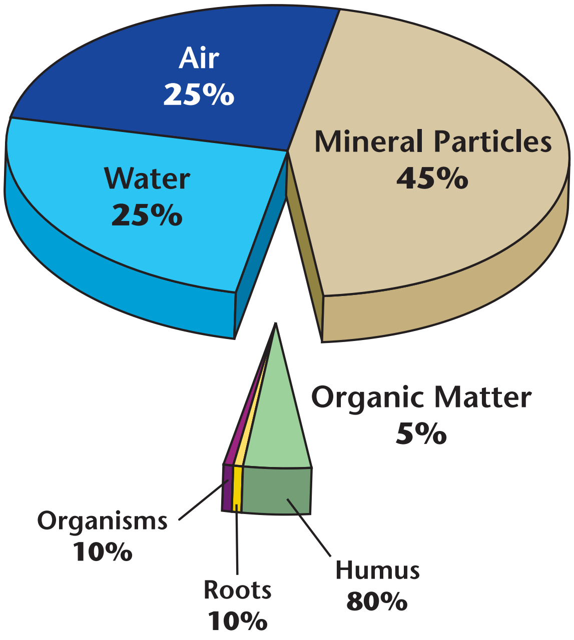


Figure A-1. Average composition of soil.
(Source: Pidwirny, M. J., *Fundamentals of Physical Geography*)

The mass of dry soil per unit of bulk volume, including the airspace, is called the soil bulk density. Bulk density is an indicator of soil quality. Soils with a high proportion of pore space to solids have lower bulk densities than those that are more compact and have less pore space. As bulk density increases, pore space is reduced, which ultimately inhibits root growth. Not only is it more difficult for roots to penetrate through the soil, fewer pores means less aeration and water infiltration both of which also deteriorate the conditions necessary for optimum crop growth. Fine-textured soils such as silt loams, clays, and clay loams generally have lower bulk densities than sandy soils. Sandy soils typically have less total pore space than finer textured soils. Sandy soils lack the micro-pore spaces that exist within soil aggregates, which finer textured soils contain in addition to the macro-pore spaces that exist between soil aggregates (Figure A-2).[1] Although finer textured soils have very low bulk densities, when they become compacted, the bulk density can be quite high.

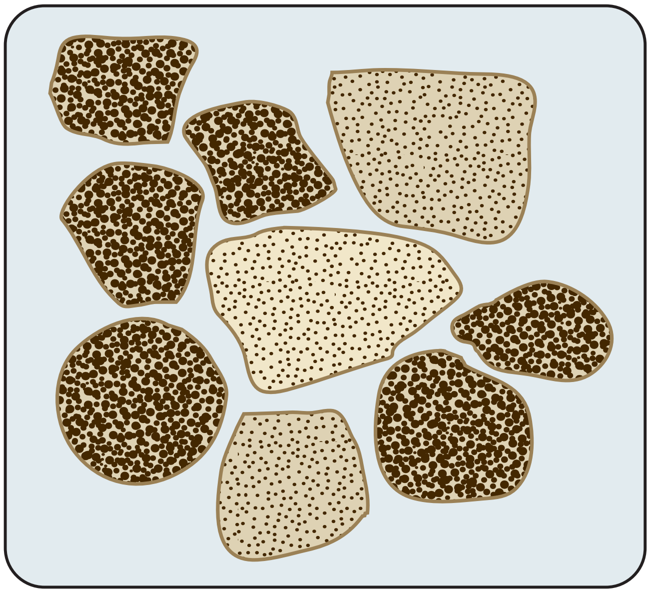


Figure A-2. Soil aggregates, aka micro & macro.

Heavy animal traffic and repeatedly driving farm equipment over fields and can compact soils, increasing the bulk density. Compaction deteriorates plant growth, and increased bulk density means a diminished capacity to infiltrate water and, therefore, greater surface runoff. It is extremely difficult to decrease the bulk density of a soil once it has been compacted. Tillage practices can initially loosen the soil surface and improve aeration and infiltration; however, over long periods those practices also lead to an overall increase in soil bulk density. The effects that different practices can have on increasing soil bulk density should be considered so that they can be minimized to improve the longevity of the soil, reduce surface runoff and help crops reach optimum yield potentials.

Soil is largely made up of mineral material from weathered rock (also called parent material), which is the product of thousands of years of physical processes. Temperature changes, water, ice and wind abrasions, and plants and animals all act to physically wear down rock and minerals. Physical weathering exposes greater amounts of surface area that can simultaneously weather through chemical processes. Many chemical reactions can take place during soil formation. Acid-producing reactions are one example that is enhanced once a soil begins supporting living organisms. Carbon dioxide is emitted through respiration and decomposition. Carbon dioxide dissolves in water held in the soil pore spaces to form carbonic acid, which dissolves minerals. Physical and chemical weathering will occur simultaneously and enhance each other, greatly speeding up the soil-forming process.

The soil-forming process produces distinct visible layers, called horizons, in the soil. The horizons are defined by the soil's color, texture, consistency, and structure. Horizons will also vary in chemical characteristics or composition. Figure A-3 shows the major horizons in a soil profile.

Some soils will have an O (organic) horizon on the surface that consists mainly of plant litter at various levels of decomposition. The O horizon is unlikely to be identified in cultivated fields because the layer is easily lost though erosion that can result from years of plowing and tilling.

Horizon A is the surface soil (also called the topsoil) and is the layer where crops are planted and grown. Typically, the layer contains more organic matter and is coarser than the lower horizons. The humus in the surface soil imparts a distinct grayish to dark-brown to black color to the horizon. Generally, the darker the color of a soil, the more humus is present. Horizon A is the zone of maximum biological activity.

Horizon B is the subsurface soil, which is also called the subsoil. There is generally more clay, which makes the horizon finer-grained than the surface horizon. Horizon B's color is usually brighter, ranging from red to brown to yellow. The layer generally accumulates all or most of the silicates, clay, iron, and aluminum in the soil.

Horizon C is formed in the parent material and has acquired some characteristics of the subsoil. The parent material can be alluvium, loess, colluvium,[2] or bedrock. If formed in bedrock, the layer will sometimes look like weathered rock, but it is soft enough to be dug into and will crumble easily.

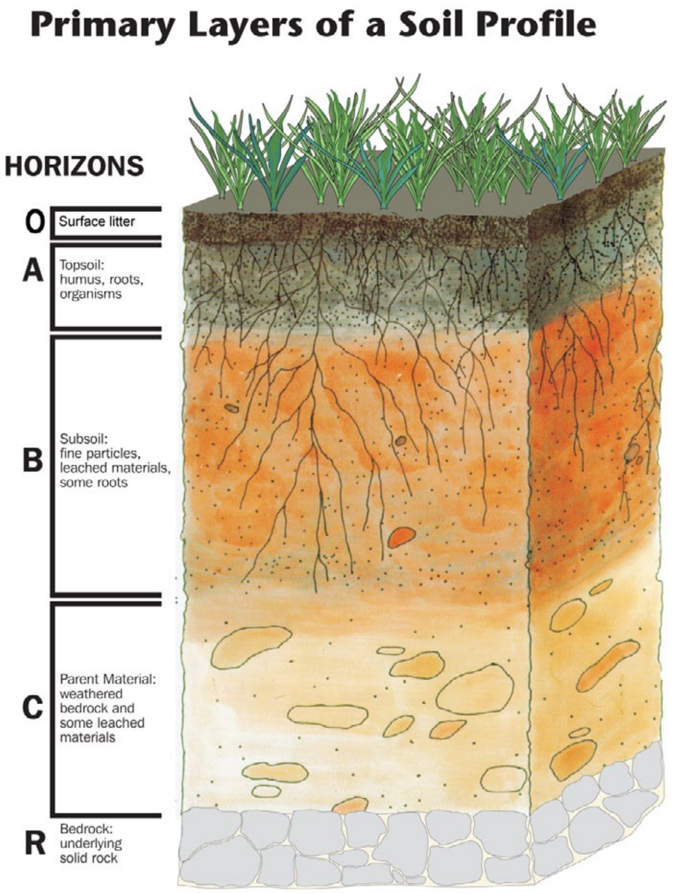


Figure A-3. The major horizons in a soil profile. (Source: Illinois Central Core)

The R horizon, if present, consists of unweathered bedrock.

Soil Properties

The properties of a soil result from the environmental factors and conditions that shaped the soil. The following characteristics are important factors that determine a soil's suitability for use and its management needs.

Organic Matter

Organic matter in soil is derived from decomposed plant and animal material. The amount of organic matter depends on the type of plants that are growing in the soil, how long the plants have been growing, and the water content or moisture in the soil. Humus is the most reactive and important component of soil organic matter.

An adequate level of humus provides soil with a number of benefits:

- Increased ability to hold and store moisture.
- Helps maintain porosity in fine-textured soils.
- Reduces leaching of soluble nutrients to lower soil layers.
- Important source of carbon and nitrogen (N) for plants.
- Improves soil structure for plant growth.
- Decreases erosion losses.

Texture

Texture refers to the fineness or coarseness of the mineral particles in the soil and is determined by the relative amounts of different sized mineral particles in the soil. Particles are normally grouped into three main classes: sand, silt, and clay (Table A-1).

Table A-1. Soil classification by particle size

Classification	Soil particle size
Sand	0.05 to 2 mm
Silt	0.002 to 0.05 mm
Clay	< 0.002 mm

Mineral particles that are larger than 2 mm in diameter are considered coarse fragments. Mineral particles that range from 0.05 mm to 2 mm in diameter are called sand. Sand feels rough when rubbed between the thumb and fingers. Soil particles between 0.002 mm to 0.05 mm in diameter are classified as silt. Dry silt feels smooth and silky and retains an imprint when pressed. Wet silt remains smooth and does not become slick or sticky. Clay is the finest sized particle, with each particle smaller than 0.002 mm in diameter. When dry, clay feels very smooth. When wet, clay becomes slick and sticky and holds its form when shaped.

The proportion of sand, silt, and clay form the basis for 12 primary classes of soil texture (Figure A-4 and Table A-2). The texture of a soil affects the movement of air and water, as well as plant root penetration. However, most importantly, the texture of a soil determines the amount of surface area available. The surface of a mineral is where water, nutrients, chemicals, microorganisms, and charges are held and released. That ultimately determines the soil's water-holding capacity and fertility. Coarse and sandy soils allow for more rapid infiltration rates for water as opposed to more fine-textured or clay soils. Sandy soils are also easier to till. Sandy soils are suited for producing specialty crops such as vegetables, tobacco, and peanuts. Fine-textured soils hold more water and

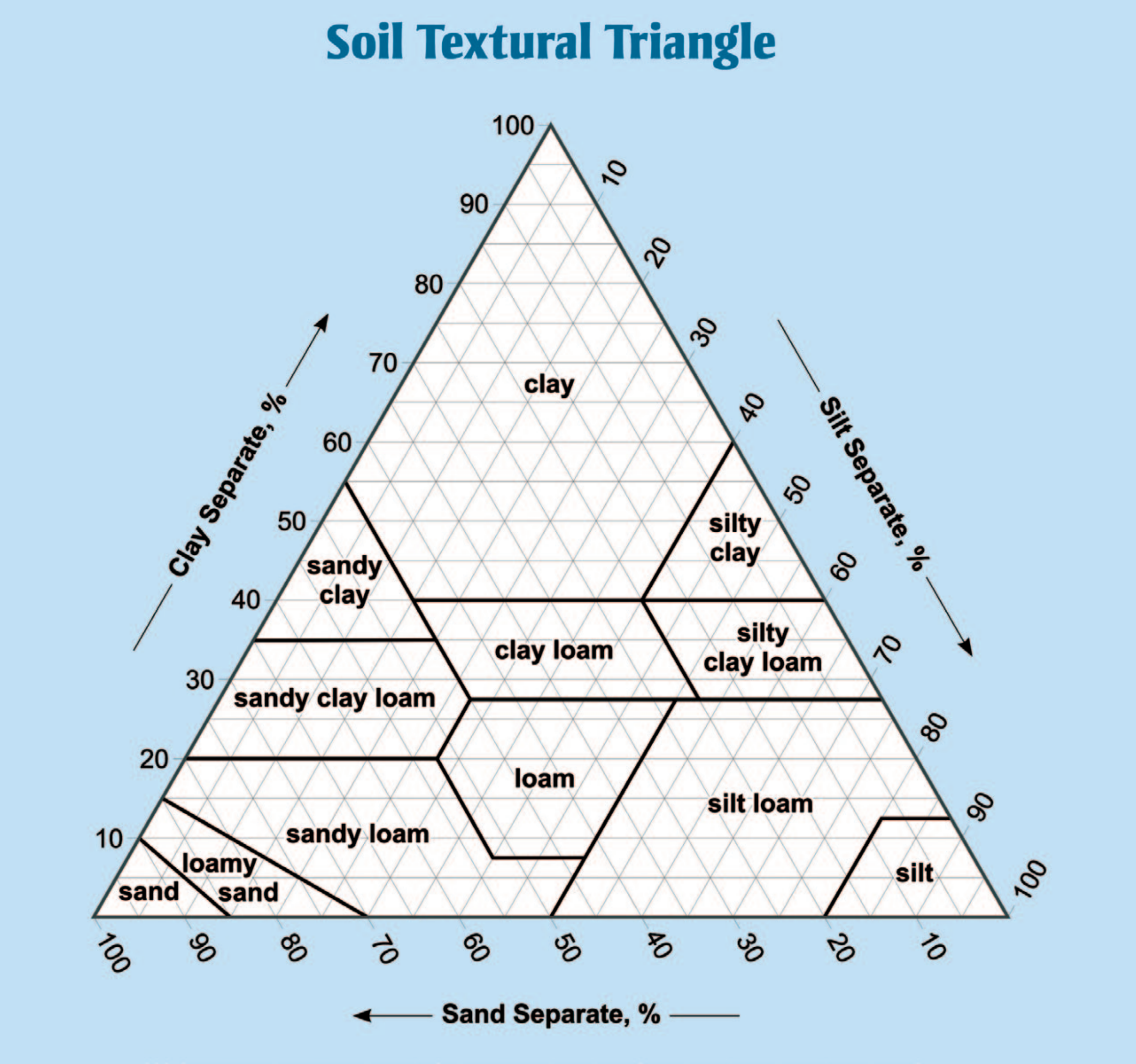


Figure A-4. Soil textural triangle. (Source: USDA/NRCS) plant nutrients and require less frequent nutrient applications. Moisture has a significant effect on the workability of fine soils. Such soils can form puddles after a rain and can develop a crust. Fine-textured soils are best suited for producing corn, small grains, hay, and forages.

Table A-2. Soil texture classes

Texture classes of soils[a]		
Common names	**Texture**	**Class names**
Sandy soils	Coarse	Sandy, loamy sands
Loamy soils	Moderately coarse	Sandy loam, loam
	Medium	Silt loam, silt, clay loam
	Moderately fine	Sandy clay loam, silty clay loam
Clayey soils	Fine	Sandy clay, silty clay, clay

[a] Adapted from Smith 1990

Aggregation and Structure

The cementing or binding together of several soil particles into a secondary unit is called soil aggregation. The soil particles are arranged or grouped together to form structural pieces (building blocks) called peds or aggregates, in various shapes and sizes. The arrangement of the aggregates determines the soil's structure (Figure A-5).

Structure is an important soil characteristic because good structure allows favorable movement of air and water and allows and encourages extensive root development.

The formation of aggregates and good structure of the surface soil is promoted by a proper supply of organic matter, adequate lime, and working or tilling the soil during correct moisture conditions. On the other hand, structure is weakened or destroyed when organic matter is depleted, when inadequate lime is used, and when the soil is tilled or worked with too much or too little moisture in the soil.

Color

The color of a soil has little influence on a soil's function; however, it tells a great deal about the soil. Soil colors are often a result of the various oxidation states of the minerals present. Brighter colors such as yellow and reds are an indication of iron oxides. The brighter colors suggest good drainage and aeration. Grayish soils can indicate iron reduction caused by permanently saturated soil. Soils with mottled colors of various shades of yellow, brown, and gray are indicative of a fluctuating aerobic and anaerobic environment. Aside from iron, other minerals that contribute to soil color are manganese oxide, glauconite, and carbonates. Additionally, very dark browns and black soil colors can be an indication of high levels of organic matter.

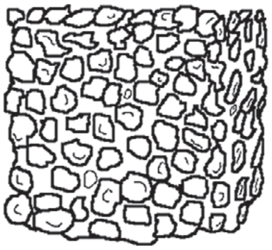
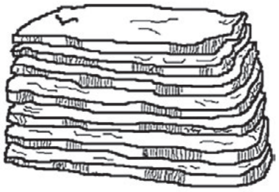
	**Granular:** Resembles cookie crumbs and is usually less than 0.5 cm in diameter. Commonly found in surface horizons where roots have been growing.
	**Platy:** Thin, flat plates of soil that lie horizontally. Usually found in compacted soil.
	**Single Grained:** Soil is broken into individual particles that do not stick together. Always accompanies a loose consistence. Commonly found in sandy soils.

Figure A-5. Examples of soil structure. (Source: Soil Science Education home page)

Retention/Water-Holding Capacity

The amount of water retained in a soil is dependent on the interaction of soil texture, bulk density, and aggregation. The term field capacity defines the amount of water remaining in a soil after downward gravitational flow has stopped, and it is expressed as a percent by weight. The permanent wilting percentage represents the amount of water in soil after plants are permanently wilted. Water is still in the soil, but it is held so tightly that it is unavailable for plant use. The difference between field capacity and the wilting point is the plant-available water (Figure A-6). Irrigation water is generally applied when the soil moisture is depleted by 40 to 60 percent of field capacity. Irrigation water is applied to bring the soil moisture back to near field capacity.

Sandy soils hold little water because their large pore spaces allow water to drain freely. While clay soils have greater water-holding capacities because of their small pore spaces, they also hold water more tightly than sandy soils, making a certain amount of water unavailable to plants. The amount of organic matter and stoniness in soils improves the available water capacity for plant use. Coarser soils tend to have the lowest plant available water capacity, while medium-textured soils tend to have the highest. Decreasing the bulk density of soils reduces water-holding capacity.

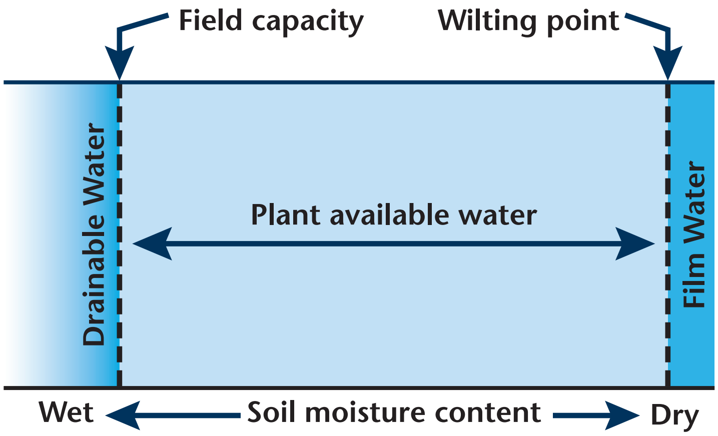


Figure A-6. Plant available water and drainable water in relation to field capacity and wilting point. (Source: University of Minnesota)

Drainage

Soil drainage is defined as the rate and extent of water removal. That includes water movement across the surface and downward through the soil. Topography is a very important factor in soil drainage. Other factors that affect drainage include the soil layers' texture and soil structure. Poor drainage is indicated by a mottled gray soil color, constantly wet soil, or water *sitting* on the soil surface for a long time after rain or irrigation. If drainage is poor, plant roots are deprived of oxygen. Thus, adequate drainage is essential to good plant growth. Conversely, excessively drained soils, such as very sandy soils or those on steep slopes, tend to hold too little water for normal plant growth.

Cation Exchange Capacity

Soil materials have a net surface charge, usually negative, that allows them to hold and retain ions (i.e., nutrients) against leaching. The net negative charge of a soil is largely attributed to the clay and organic matter in the soil and will naturally attract positively charged nutrients and repel negatively charged nutrients. That explains why cations, the positively charged nutrients (such as ammonium (NH_3^+)), remain in the soil while anions, the negatively charged nutrients (such as nitrate (NO_3^-)), are repelled and easily leached out of the soil.

The cation exchange capacity (CEC) is a measure of the soil's ability to retain cations and, therefore, is indicative of the soil's fertility. In addition to clay and organic matter, pH has an effect on CEC. Increasing soil pH increases its CEC, activating more ion exchange sites.

Soils with low CEC can have one or more of the following characteristics:

- High sand and low clay content.
- Low organic matter content.
- Low water-holding capacity.
- Low pH value.
- Lightly buffered and cannot easily resist changes in pH or other chemical changes.
- Nutrients are leached very easily.
- Productivity can be low.
- Certain types of clay such as kaolinite will have a much lower CEC than a montmorillonite or vermiculite (high shrink and swell clays).

Soils with a higher CEC can have one or more of the following characteristics:

- Low sand and high clay content.
- Moderate to high organic matter content.
- High water-holding capacity.
- Highly buffered and resist changes in pH or other chemical changes.
- Nutrients are retained and leaching losses reduced.

A soil's CEC directly affects the amount of fertilizer that should be used and the frequency with which it should be applied.

Soil Fertility

Soil fertility is the ability of a soil to provide nutrients for plant growth (Table A-3). Many factors affect the availability of elements in soil, including the form of the element found in the soil, pH, soil aeration, soil compaction, soil temperature, and soil moisture. As described, the ability of a soil to retain nutrients is related to its CEC. Many of the important plant nutrients are cations, which are retained by the soil's negative charge. Those include ammonium (NH_4^+), calcium (Ca^{2+}), potassium (K^+), sodium (Na_2^+), aluminum (Al^{3+}), hydrogen (H^+), and magnesium (Mg^{2+}). As the CEC increases, the soil's ability to retain and provide nutrients to plants increases. Therefore, the fertility and productivity of a soil can be greatly influenced by the CEC. Negatively charged ions, or anions, are leached than positively charged ions. For example, NO_3^- is not retained in the soil profile because of its negative charge. An exception occurs with phosphorus (P). Although it exists in the anionic form, the properties of phosphate anions allow them to (1) react with other minerals in the soil and form low-solubility compounds that are unavailable to the plant and (2) to become fixed on and in available sites of clay particles through a process known as phosphorus fixation. Thus, phosphorus leaching is limited unless soil concentrations become very high or in sandy soils because of limited fixation sites.

Table A-3. Essential plant nutrients

Plant-available forms of essential elements	
Primary plant nutrients	
Nitrogen	NH_4^+, NO_3^-
Phosphorus	HPO_4^{2-}, $H_2PO_4^-$
Potassium	K^+
Secondary plant nutrients	
Calcium	Ca^{2+}
Magnesium	Mg^{2+}
Sulfur	SO_4^{2-}
Carbon	CO_2
Hydrogen	H^+, OH^-

Soil pH affects plant nutrient availability because pH greatly influences the solubility of certain elements. Most crops grow best in slightly acidic soils (pH 6.0 to 6.5). Acidification is a natural and continuous process in many soils. Through chemical weathering, cations are released from parent materials and become available on the exchange complex of a clay particle. Soils become acidic when the cations are displaced by acid ions, mostly H^+ and Al^{3+}. Acid ions are prevalent in the soil because of other ongoing chemical processes in the soil that release them. When exposed to water, the non-acidic cations (K^+, Ca^{2+}, and Mg^{2+}) and anions are leached from the soil profile, leaving the exchange complex and soil solution acidic. In areas with high annual rainfall, soils tend to be acidic because of the increased leaching conditions. For that reason, soils in Eastern states are generally more acidic than those in the Midwest and Western United States.

The working of ground limestone into the soil to raise soil pH is referred to as liming. The benefits of liming are both direct and indirect. Some direct benefits include the reduction of Al^{3+} and Mn^{2+} solubility (both ions are toxic to most plants unless at very low concentrations), and the application of Ca^{2+} and/or Mg^{2+}, both of which are plant nutrients. Indirect benefits include increased microbial activity and the increased Ca^{2+} levels in the soil can improve the soil structure. The benefits of liming are generally expected to last for at least 5 and commonly up to 10 years. While liming has many beneficial effects, over liming can easily induce micronutrient deficiencies in many crops adapted to low or moderate pH conditions.

For a plant to take up nutrients, the nutrient must exist in the soil solution (water-filled pore space) and be in a soluble form. A large amount of nutrients are stored in the solid framework (mineral and organic material) of a soil; however, the nutrients are released slowly to the soil solution through chemical and biochemical processes. The soil solution usually holds insufficient quantities of nutrients for plant's nutritional needs. The larger particles (sand, silt, large clay particles, and organic matter), tightly entrap and retain certain nutrient species making them available very slowly over time. Within the colloidal size fraction, nutrients are exposed to a greater surface area and broken down faster, but they are still entrapped and, thus, are only slightly more available. Nutrient ions are also adsorbed to mineral surfaces, in what is considered an exchangeable form, but the nutrients are also only moderately available. It is only when they reach the soil solution that nutrients are free and available for plant uptake and considered *plant available*.

In addition nutrients being plant available, nutrients must be at the root surface for uptake. If nutrients are not in direct contact with the root, they must move by mass flow or diffusion. Root uptake of nutrients is an active metabolic process. Therefore, even if adequate plant-available nutrients are present, factors that deter flow and root metabolism, such as soil compaction, cold temperatures, lack of water or oxygen, can inhibit plant uptake of nutrients.

Forms and Fate of Nitrogen

Nitrogen is an essential part of amino acids, the building blocks for proteins, making it an important plant nutrient. In the soil, it exists in both organic (proteins, amino acids, urea, in living organisms and decaying plant and animal tissues) and inorganic forms [ammonium (NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-), and ammonia ($NH_{3(gas)}$)]. The majority of nitrogen in the soils is in an organic form (95 to 99 percent as amine groups in proteins), which is largely unavailable for plant uptake. Figure A-7 illustrates the processes responsible for converting nitrogen into plant available forms.

Microbes break down organic compounds releasing ammonium ions through a process called mineralization. Mineralization occurs as a result of decomposition. The factors that control decomposition control the rate of mineralization and, therefore, the rate at which plant available nitrogen is released to soil. Factors controlling decomposition include soil conditions that encourage microbial growth and the carbon:nitrogen (C:N) ratio of the compound that is being degraded. Adequate soil moisture and aeration, near-neutral soil pH, and warm soil temperatures are conditions that are favorable to a broad range of organisms.

Microbes need carbon, but they also require nitrogen for building cells and extracting energy. The C:N ratio of the compound being decomposed is a critical factor in determining if nitrogen is utilized by the microbes for energy and depleted from the soil or supplied to the plant available nitrogen pool in the soil. When materials with a high C:N ratio, such as corn stalks (C:N ratio is typically 55:1) are added to soil, microorganisms begin to degrade the compound as a food source. Given the limited amount of nitrogen in the source itself, the microbes will scavenge the soil for available nitrogen, which is necessary for decomposition. In such situations, the soil can be depleted of plant available nitrogen. On the other hand, when an organic compound with a low C:N ratio, such as alfalfa hay (C:N ratio is typically 13:1) is added to soil, there is sufficient nitrogen in the compound itself for decomposition. The microbes do not need to use nitrogen from the

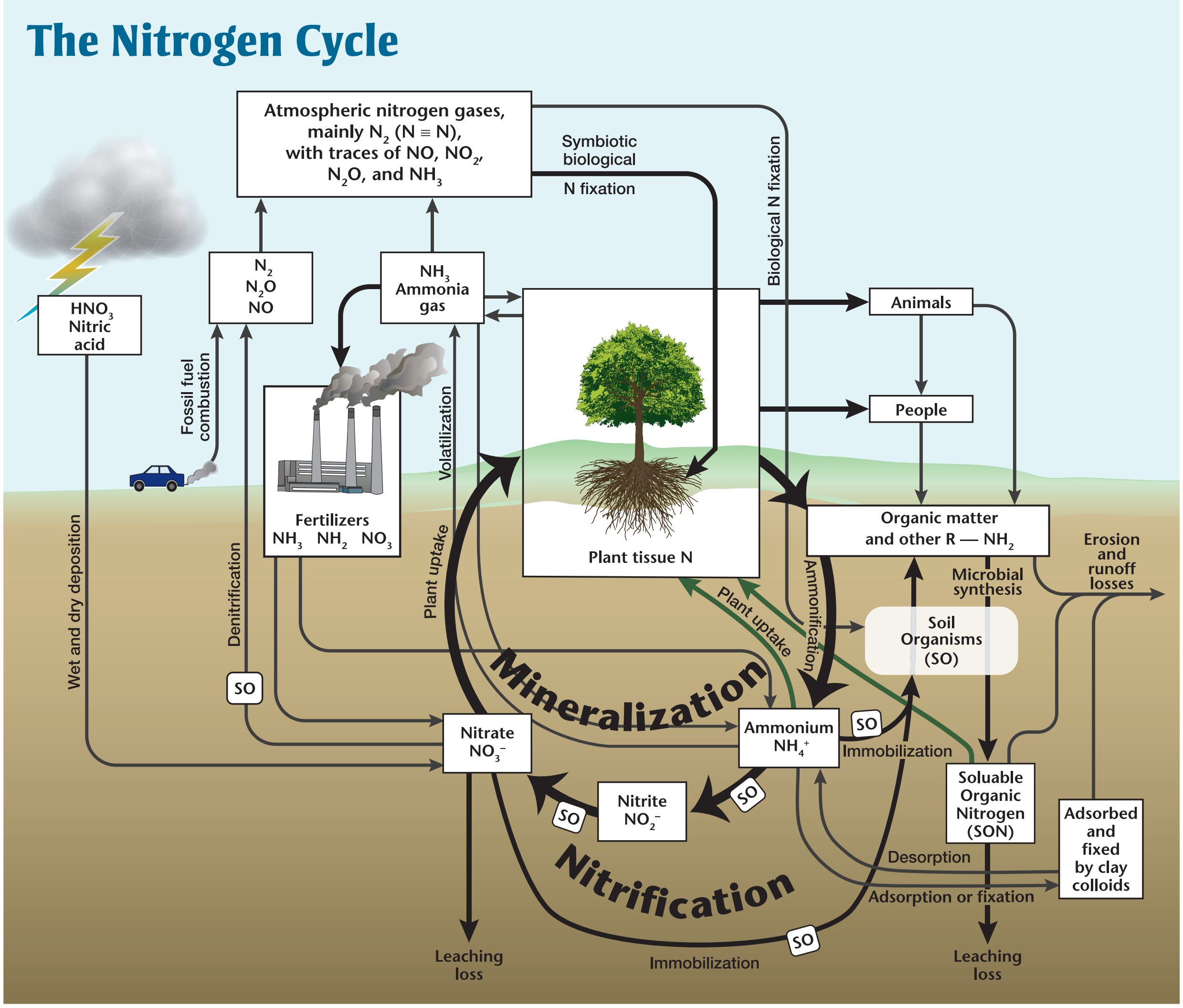


Figure A-7. The Nitrogen Cycle.

soil. Rather, decomposition of the material can release plant available nitrogen from the organic compound to the soil.

As mineralization occurs, if ammonium is released to the soil, it can be directly absorbed by a plant or it can be oxidized to nitrate and then absorbed. Because soil systems often are aerobic, ammonium does not typically persist in the soil in large quantities. Ammonium is a positively charged ion, which means, if it is present in a soil, it can be retained by the negatively charged soil particles on a soil's exchange complex. As previously mentioned, nutrients held on the mineral exchange complex are moderately plant available because, while they are retained on the mineral surface, they can be displaced by competing ions to the soil solution. Ammonium can also become fixed within the crystal structure of certain types of clay particles because of its size and the arrangement of the specific clay particles. Fixed ammonium is only slowly released to the soil solution and would not be a sufficient source of nitrogen for plants.

When manure is land applied as an organic compound, only a small fraction of the nitrogen might be soluble as ammonium and plant available. However, a larger portion of that nitrogen is mineralized by microbes and slowly released over many years. Nitrogen mineralization rates of the organic nitrogen present in the initial land application vary depending on various environmental factors such as soil type, the manure source, and climate. For example, cattle manure mixed with bedding that has been stored under cover will have approximately 60 percent of the organic nitrogen fraction mineralized in the year of application; 6 percent in the second year, and 2 percent in the third year. For many types of manure, 1 to 4 percent of organic nitrogen is still being released 4 years after the initial application. Therefore, calculations to determine annual land applications of nitrogen should account for released forms of nitrogen from previous organic nitrogen applications.

As nitrogen-containing organic compounds such as manure and fertilizers are broken down, ammonia can be released. Ammonia is most commonly found as a gas and is released from a soil system through a process called volatilization. Volatilization occurs at the liquid air interfaces and is controlled by the pH and water content of the soils, which drive nitrogen either into or out of the soil. The loss of ammonia to the atmosphere is driven by high level pH soils. The importance of incorporating manures into soils is to minimize the contact area between the manure and the ambient air to reduce ammonia volatilization. Soils and plants have the ability to sorb ammonia from the atmosphere, but fertilizer recommendations do not consider atmospheric nitrogen sources. As a result, areas that are exposed to high atmospheric ammonia concentrations (such as intensive livestock operations) could be having fertilizers applied at rates in excess of plants' needs.

Nitrate is another plant available form of nitrogen that can enter the soil system through atmospheric deposition, commercial fertilizers, and transformation of ammonium as mentioned above. Ammonium is oxidized to nitrite, which is quickly oxidized to nitrate by nitrifying bacteria as long as favorable soil conditions exist for the bacteria to survive. Nitrite is also plant available, but it can be toxic to plants and rarely persists in the soil in significant concentrations. As opposed to ammonium, nitrate is a negatively charged ion that is not adsorbed to the negatively charged soil mineral surfaces. Therefore, nitrate is readily available to plants, but if excess nitrate persists in the soil solution, the negatively charged nutrient is repelled by the soil surfaces and lost to groundwater through leaching. Factors that contribute to nitrogen leaching or runoff include over-application of nitrogen as fertilizers or manure particularly on sandy or coarse-textured soils; improperly timed applications of nitrogen, poorly designed or nonexistent soil conservation measures; and periods of exceptionally heavy rainfall.

Anaerobic bacteria can also reduce nitrate to nitrogen gas through a process called denitrification. Denitrification is a series of bacteria driven reduction reactions that reduce nitrate ultimately to nitrogen gas. Because denitrification is a reduction reaction, it requires an anaerobic environment, such as saturated soils. Only when soil oxygen levels are low enough, typically in waterlogged or poorly drained soils, will nitrate be fully reduced resulting in the formation of nitrogen gas. When oxygen levels fluctuate, as they commonly do in the field, nitrate will not be fully reduced and nitric oxide (NO) and nitrous oxide (N_2O) can be released to the atmosphere because those are intermediate by-products.

Forms and Fate of Phosphorus

Phosphorus is an important plant nutrient because it is an essential component of deoxyribonucleic acid (DNA), ribonucleic acid (RNA), and the nucleotide adenosine 5'-triphosphate (ATP), which are necessary for intracellular energy transfer. Unlike nitrogen, gaseous forms of phosphorus seldom exist and are often not considered in the phosphorus cycle (Figure A-8).

Organic phosphorus usually occurs in microbial biomass and organic matter compounds. Inorganic phosphorus commonly appears in the form of phosphates (HPO_4^{-2} and $H_2PO_4^{-}$). Relative to other nutrients, phosphorus in soil solution is found in very low concentrations (0.001 to 1 mg/L) that rarely exceed 0.01 percent of total soil phosphorus.

When phosphate ions are added to a soil, they are quickly (within hours) removed from solution to form phosphorus containing compounds with very low solubility. Phosphate most commonly forms compounds with either calcium or iron and aluminum (sometimes manganese). Initially, some ions are retained on the exchange complex, which makes them moderately plant available but with time, they undergo sequential reactions that continually decrease their solubility.

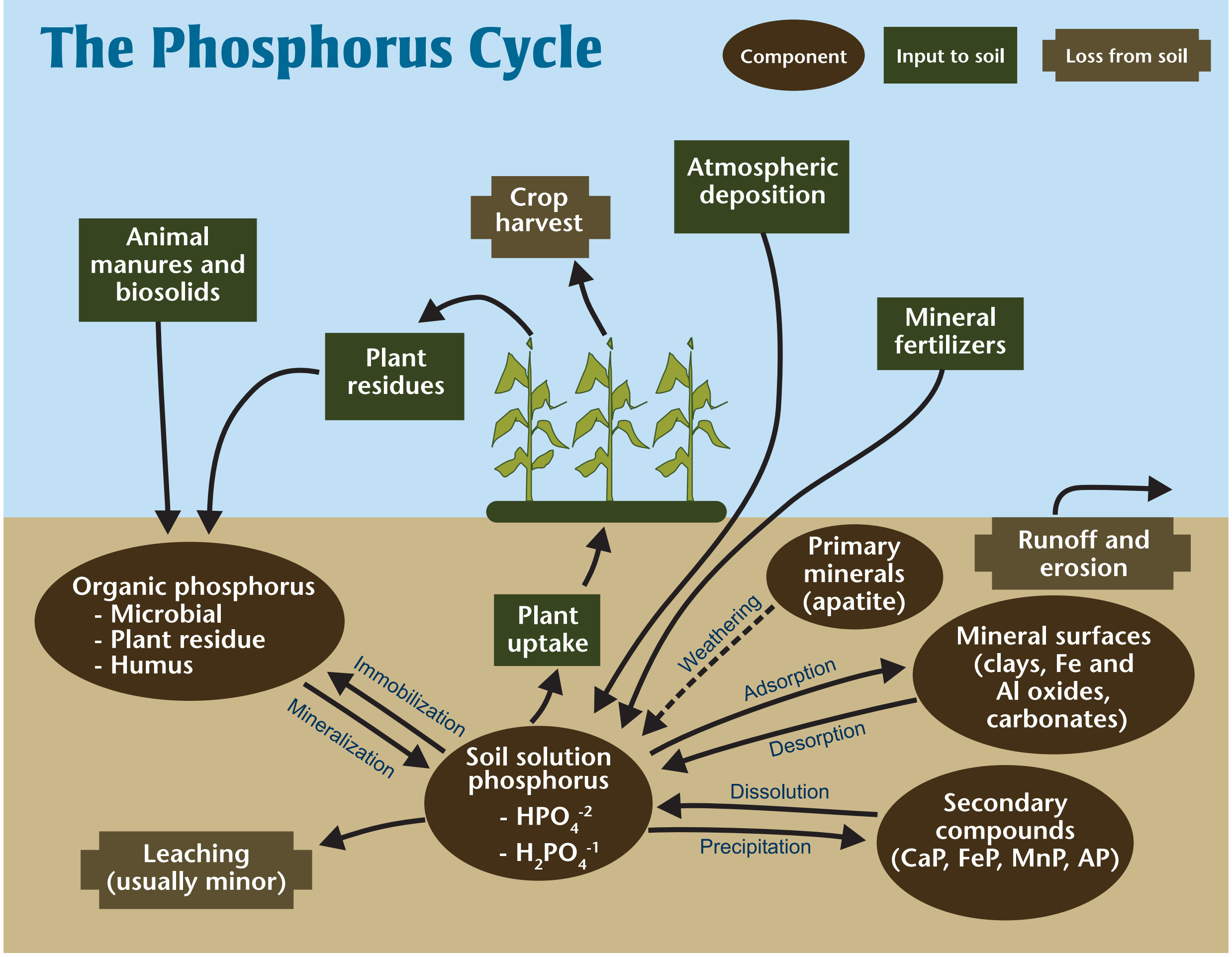


Figure A-8. The Phosphorus Cycle.

Such reactions result in phosphorus permanently bonding to the calcium or aluminum/iron/manganese ions, becoming buried under products from additional precipitation reactions. Those reactions can also entrap phosphorus within the calcium or iron/aluminum/manganese particles. That is regarded as phosphorus fixation and it is not easily reversible.

The capacity for soils to fix phosphorus depends on a number of soil factors including the mineral type, pH, and amount of organic matter. Phosphate ions are negatively charged; therefore, the minerals sorbing and fixing the ions must be positively charged. Certain types of minerals have a greater capacity for sorbing anions than others. The pH of the soil affects the solubility of the calcium and iron and aluminum phosphate compounds with the greatest fixation occurring at low and high pH values. Organic matter and by-products from its decomposition compete with phosphate ions for adsorption sites on mineral surfaces; therefore, soils with low organic matter concentrations tend to fix more phosphorus, making less available to plants. Because fixation depends on available mineral surface area and sorption sites, soils have a finite capacity to fix phosphorus.

Additions of fertilizers and manures typically allow for only 10 to 15 percent of added phosphorus to be taken up by plants because of that fixation capacity. Therefore, during the early and mid-20th century, farmers applied phosphorus in quantities far in excess of the plants' nutritional needs. In addition, manure has historically been applied at rates to meet plant nitrogen requirements, which can supply 2 to 4 times the phosphorus requirement. What was not removed in the harvest could accumulate in the soil in an insoluble, unavailable form. That became common practice and over the years, many fertilized, cultivated soils have reached their phosphorus fixation capacity. Note that that was not the case everywhere. In many developing countries where fertilizer is seldom used, phosphorus is often the limiting nutrient in food-crop production.

If not taken up by plants, phosphorus can be lost with surface runoff as dissolved phosphorus (if not incorporated into a soil) or it can be lost with soil particles through erosion or colloid leaching if sorbed to mineral surfaces. Soil particles containing fixed phosphorus that are lost through erosion might not appear to degrade water quality because of phosphorus fixation. However, in prolonged anaerobic environments (i.e., river beds) iron that is binding phosphorus will be reduced. While oxidized iron is insoluble, reduced iron is soluble allowing for the bound phosphate to be released into solution, contributing to water quality problems like eutrophication.

Water Quality

Water pollution from cropland is controlled in large part by the hydrologic cycle. Precipitation and irrigation add water, which, once at the soil surface, infiltrate, pond, or run off. Two types of losses from soils that affect water quality are (1) percolation or drainage, and (2) runoff. Percolation results in the loss of soluble elements (leaching), thus depleting soils of certain nutrients. Runoff losses generally include water and appreciable amounts of soil (erosion).

Two prime reasons raise concern over the loss of essential elements by leaching and erosion. First is the obvious concern for keeping nutrients in the soil so that they are available to crops. A second and equally significant reason is to keep the nutrients out of streams, rivers, and lakes. Nitrate contamination of ground and surface waters can cause serious environmental damage. Nitrates in drinking water are toxic because they reduce the capacity for blood to carry oxygen. That can be lethal to human infants and can alter normal body functioning in adults. Some underground sources of drinking water have become sufficiently high in nitrate causing health concerns for humans. Likewise, surface runoff waters from heavily fertilized lands can contain levels of nitrate toxic to livestock. While phosphorus is not toxic, it can degrade water quality if lost from a soil system in significant quantities. Excessive growth of algae and other aquatic species takes place in water overly enriched with nitrogen and phosphorus. That process, called eutrophication, depletes the water of its oxygen, thus harming fish, other aquatic species, and ultimately most life in the waterbody.

Infiltration, Percolation, and Leaching

As water enters a soil (infiltration) and moves down through the soil profile (percolation) it carries dissolved nutrients with it (leaching). Leaching losses occur when the amount of rainfall or irrigation water entering a soil exceeds the soil's ability to store it. The amount and rate of nutrient losses are influenced by the amount of rainfall or irrigation, the topography of the landscape, the amount of evaporation, the soil type, and the crop cover.

Soil properties have an effect on nutrient leaching losses. The physical properties of sand, silt, and clay, and the relative proportions of each have direct bearing on nutrient retention. As discussed, coarse soils (soils with a high percentage of sand) generally permit greater nutrient loss than do finer textured soils (soils with higher percentage of silt and clay). Organic matter content and type and amount of clay have significant influence on retention and nutrient storage and exchange.

The loss of nutrients through leaching is also influenced by climatic factors. In regions where water percolation is high, the potential for leaching is also high. Such conditions exist in the United States in the humid east and in the heavily irrigated sections of the west. In non-irrigated, semiarid areas, less nutrient leaching occurs because less water is added to the soil to contribute to the leaching process.

The proportion of rain or irrigation water entering the soil is enhanced by practices that keep the soil surface covered (e.g., with vegetation or mulch) to protect it from the beating action of rain drops that breaks down soil surface structure, decreasing porosity. Rain on bare soil also displaces soil particles that are easily transported by surface runoff.

Numerous best management practices are available to encourage residue management and to minimize negative consequences of soil tillage. Excessive tillage that destroys the surface roughness should be avoided. Tillage across the slope, leaving small ridges, encourages water infiltration. Likewise, terraces can help control the erosive potential of water movement and increase infiltration into the soil.

Runoff and Erosion

A primary principle of soil water management is to encourage water movement into rather than off the soil. The more water runs off the surface, the less infiltrates into the soil. Maintaining good soil structure is critical to reducing runoff; excess water that cannot infiltrate the soil accumulates on the surface and flows downgrade displacing surface soil particles along the way (erosion). Soil erosion damages productive soils and can increase nutrient transport to streams and lakes.

Two steps are recognized in the erosion process—the detachment or loosening influence and transportation by floating, rolling, dragging, and splashing. Freezing and thawing, flowing water, and rain are the major detaching agents. Those actions displace soil particles that are easily transported by surface runoff. Raindrop splash and especially running water facilitate the transport of loosened soil.

Following detachment, three types of water erosion are recognized: sheet, rill, and gully. In sheet erosion, soil is removed more or less uniformly from every part of the slope. However, sheet erosion is often accompanied by tiny channels (rills) irregularly dispersed, especially on bare land newly planted or fallow. That is called rill erosion. The rills can be obliterated by tillage, but the damage is already done—the soil quality in the field is diminished.

Where the volume of runoff water is further concentrated, downward cutting forms larger channels or gullies. That is called gully erosion. The gullies are obstacles to tillage and cannot be removed by ordinary tillage practices. While all types can be serious, the losses from sheet and rill erosion, although less noticeable, are responsible for most of the field soil deterioration.

The quantity of nutrients lost from the soil by erosion can be quite high. Such losses can be counterbalanced only in part by adding fertilizers; even still soils that are severely eroded might not respond well to fertilization. Much of the nitrogen and phosphorus lost is in eroded sediments, which include soil organic matter and finer particles.

Revised Universal Soil Loss Equation Version 2[3]

The Revised Universal Soil Loss Equation, Version 2 (RUSLE2), is designed to predict the long-term average rate of soil loss and guide conservationists on proper cropping, management, and conservation practices for a field or management unit. RUSLE2 cannot be applied to a specific storm or a specific year. Agricultural research coupled with centuries of farmers' experience has identified the major factors affecting erosion.

RUSLE2 is a computer model that uses a detailed mathematical approach for integrating multiple equations that describe how factors such as plant yield, vegetative canopy and rooting patterns, surface roughness, mechanical soil disturbance, amount of biomass on surface, and others affect soil erosion. The basic structure of the RUSLE2 equation is

$$A = RKLSCP$$

where

A = predicted average annual soil loss from rill and inter rill erosion caused by rainfall and its associated overland flow expressed in tons/acre/year.

R = climatic erosivity.

K = soil erodibility measured under a standard condition.

L = slope length.

S = slope steepness.

C = cover and management.

P = support practices (erosion control).

RUSLE2's predicted soil losses can be compared with soil loss tolerances (T) to provide guidelines for effective erosion control.

Soil Loss Tolerance

Soil loss tolerance (T) is the maximum amount of soil loss in tons per acre per year that can be tolerated and still permit a high level of crop productivity to be sustained economically and indefinitely.

A Natural Resources Conservation Service conservation plan is essentially a set of conservation practices that are designed to work in an integrated manner to accomplish an identified level of resource treatment. Developing a conservation plan involves determining the baseline erosion and other associated losses and evaluating the practices that would meet T.

RUSLE2's user interface allows a user to select from its database values to describe site-specific field conditions for climate, soil, topography, and land use. A brief description of each factor and the extent of its influence on soil erosion follows:

> Rainfall erosivity, the R factor, is the most important climatic variable used by RUSLE2. Erosivity is related to rainfall amount and intensity, with the latter generally being more influential. A high annual precipitation received in a number of gentle rains can cause little erosion, whereas a lower yearly rainfall descending in a few torrential downpours can result in severe erosion. Temperature is also a key variable as rain and temperature affect the longevity of materials like crop residue and mulch that can prevent erosion. RUSLE2 associates erosivity, precipitation, and temperature values with the location chosen by the user.
>
> The soil erodibility factor, K, indicates the inherent erodibility of a soil. The two most significant and closely related soil characteristics affecting erosion are infiltration capacity and structural stability. The infiltration capacity is influenced greatly by structural

stability, especially in the upper soil horizons. In addition, organic matter content, soil texture, the kind and amount of swelling clays, soil depth, tendency to form a surface crust, and the presence of impervious soil layers all influence the infiltration capacity.

The stability of soil aggregates affects the extent of erosion damage in another way. Resistance of surface granules to the beating action of rain saves soil even though runoff does occur. The granule stability of some tropical clay soils accounts for the resistance of those soils to the action of torrential rains. Downpours of a similar magnitude on temperate region clays would be disastrous.

Values used by RUSLE2 for soil erodibility have been determined for most cropland and similar soils across the United States by the U.S. Department of Agriculture–Natural Resources Conservation Service. The user typically selects a soil-map unit name from a list of soils in the RUSLE2 database.

Site-specific values are entered for the topographic factor (*LS*), which reflects the influence of slope length, steepness, and shape characteristics. The greater the steepness of slope, other conditions being equal, the greater the erosion, partly because more water is likely to run off but also because of increased velocity of water flow. The length of the slope or flow path is important because it is directly proportional to the concentration of the flooding water.

Land use is the most important factor affecting rill and interrill erosion because it can be easily changed to reduce erosion. RUSLE2's cover-management (cultural) practices and support practices data are used to describe land use.

Soil detachment and erosive forces can be affected by cover-management practices. The cover and management factor, *C*, indicates the influence of cropping systems and management variables on soil loss. C is the factor over which the farmer has the most control. The type of crop, yield level, and tillage system used are important features to consider when land is used for crops. Forests and grass provide the best natural protection known for soil and are about equal in their effectiveness, but forage crops, both legumes and grasses, are next in protective ability because of their relatively dense cover. Small grains such as wheat and oats are intermediate and offer considerable obstruction to surface wash. Row crops such as corn and soybeans offer relatively little cover during the early growth stages and thereby encourage erosion. Most subject to erosion are fallowed areas where no crop is grown and all the residues have been incorporated into the soil. The marked differences among crops in their ability to maintain soil cover emphasize the value of appropriate crop rotation to reduce soil erosion.

RUSLE2 stores the description of any cover-management practice within its database and allows for selection of the practice that best fits site-specific field conditions. Key variables like yield level or mulch application can be changed so that the practice stored in RUSLE2 more accurately reflects the field conditions.

The support practice factor, *P*, reflects the benefits of contouring, strip cropping, terraces, diversions, small impoundments and other supporting factors. Such support practices reduce erosion primarily by reducing the erosivity of surface runoff. *P* is the ratio of soil loss with a given support practice to the corresponding loss when crop culture is up and down the slope. Like cover-management practices, support practices are selected from the RUSLE2 database and site-specific information such as the location of a practice is entered as required.

References

Brady, N.C., and R.R. Weil. 2002. *The Nature and Properties of Soils*. 13th ed. Pearson Education, Upper Saddle River, NJ.

Smith, R.L., and T.M. Smith. 1990. *Ecology and Field Biology*. Pearson Education, Upper Saddle River, NJ.

USDA-NRCS (U.S. Department of Agriculture, Natural Resources Conservation Service). 2011. *National Soil Survey Handbook*, title 430-VI. <*http://soils.usda.gov/technical/handbook/*>. Accessed November 11, 2011.

Endnotes

[1] Soil aggregrates – Groups of soil particles that bind to each other more strongly than to adjacent particles. The space between the aggregates provide pore space for retention and exchange of air and water.
(Definition from USDA: *http://soils.usda.gov/sqi/publications/files/sq_eig_1.pdf*.)

[2] Alluvium – A general term for all detrital material deposited or in transit by streams, including gravel, sand, silt, clay, and all variations and mixtures of these. Unless otherwise noted, alluvium is unconsolidated.
Loess – Material transported and deposited by wined and consisting of predominantly silt-sized particles.
Colluvium – A deposit of rock fragments and soil material accumulated at the base of steep slopes as a result of gravitational action (from Brady and Weil 2002).

[3] Adapted from USDA-NRCS 2011.