Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 154, Pages 21-47, April 2015

An Introduction to Soil Concepts and the Role of Soils in Watershed Management

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Abstract: Soil is a non-renewable dynamic natural resource that is essential to life. Water movement, water quality, land use, and vegetation productivity all have relationships with soil. This article introduces many important soil concepts including development, classification, properties (physical, chemical, and biological), quality, and conservation. A general understanding of soil concepts and these interwoven relationships is essential to making sound land management decisions.

Keywords: *soil conservation, soil developoment, soil disturbance, soil management, soil properties, soil quality, soil taxonomy*

Soil plays a vital role in sustaining life on the planet. Nearly all of the food that humans consume, except for what is harvested from marine environments, is grown in the Earth's soils. Other obvious functions that soils provide humans include fiber for paper and clothing, fuelwood production, and foundations for roads and buildings. Less obvious functions that soils serve are providing a medium to attenuate pollutants and excess water, groundwater recharge, nutrient cycling, and habitat for microorganisms and biota. Soils also have many secondary uses such as ingredients in confectionaries, insecticides, inks, paints, makeup, and medicines; uses of clays range from drilling muds, pottery, and artwork, to providing glossy finishes on various paper products.

Soil is a critical component of nearly every ecosystem, but is often taken for granted. Soil can be thought of as the ecosystem foundation, as soil productivity determines what an ecosystem will look like in terms of the plant and animal life it can support. For example, in forest ecosystems, soils can determine species composition, timber productivity, and wildlife habitat, richness, and diversity. The role soil plays in forests is also critical to maintaining water quality and long-term site productivity. In cultivated fields, soil quality plays a significant role in crop productivity since soil nutrients and soil physical properties can directly impact yields. In urbanized areas, soil plays a vital role in reducing runoff through infiltration and nutrient attenuation. The value of soil is easily overlooked until soil quality becomes degraded and the critical services the soil once provided are diminished.

Soil Overview

Soil Defined

The definition of soil is relative to the function it provides to the person(s) defining it. From a morphological stance, the Natural Resource Conservation Service (NRCS) defines **soil** as: "a natural body comprised of solids (minerals and organic matter), liquid, and gases that occurs on the land surface, occupies space, and is characterized by one or both of the following: horizons, or layers, that are distinguishable from the initial material as a result of additions, losses, transfers, and transformations of energy and matter or the ability to support rooted plants in a natural environment" (Soil Survey Staff 2014a). The Soil Science Society of America (SSSA) defines **soil** in terms of its genetic and environmental factors: Soil is "[T]he unconsolidated mineral or organic matter on the surface of the Earth that has been subjected to and shows effects of genetic and environmental factors of: climate (including water and temperature effects), and macro- and microorganisms, conditioned by relief, acting on parent material over a period of time. A product-soil differs from the material from which it is derived in many physical, chemical, biological, and morphological properties and characteristics" (SSSA 2008).

The Soil Profile

The vertical section of soil that shows the presence of distinct horizontal layers is known as the **soil profile** (SSSA 2008). The term **horizon** refers to the individual or distinct layers within the soil profile. Most soils are composed of several horizons (Figure 1). Typically, horizons of a soil profile will follow the topography of a landscape. Designation of horizon boundaries also comes from measurements of soil color, texture, structure, consistence, root distribution, effervescence, rock fragments, and reactivity.

The uppermost layer, the **O horizon**, consists primarily of organic material. Forested areas usually have a distinct O horizon. However, in some settings such as a grassland or cultivated field, there may be no O horizon present. Factors such as erosion or constant tillage contribute to the lack of organic matter. The O horizon has three major sub-classifications, or subordinate distinctions (designated by the lowercase letter): hemic (Oe), fibric (Oi), and sapric (Oa). The hemic layer consists of decaying material that is slightly decomposed, yet the origin is still identifiable. The fibric layer is composed of organic material that is slightly more decomposed and unidentifiable, but is not decayed entirely. The sapric layer consists of fully decomposed material whose origin is completely unidentifiable.

The **A horizon** is a mineral horizon that is formed at or just below the soil surface. It is commonly referred to as the "surface soil." Some characteristics of an A horizon may include the accumulation of organic matter and/or the presence of a plow pan. A plow plan (or plow layer) is a common characteristic of soils that have undergone conventional tillage at some point in recent time. The darkness of the A horizon can sometimes be attributed to the movement of organic matter from the overlying O horizon. Soils under intense cultivation will incorporate materials that would normally be considered part of the O horizon. These organic materials also contribute to the A horizon leading to a higher organic content than other horizons.

The **E horizon** (eluvial layer) is a common mineral horizon in forest soils that is distinguished by its lack of clay, iron (Fe), or aluminum (Al). The loss of the above materials is known as **eluviation**, which entails that these substances and dark minerals have been stripped from the soil particles. Clay, Fe, and/or Al are removed from the E horizon via leaching, which causes its light color compared to the adjacent horizons. **Leaching** is the loss of nutrients from the root zone due to the movement of water through the soil profile. The E horizon is comprised of concentrations of quartz, silica, or other minerals that are less susceptible to leaching.

The **B horizon**, known as the "zone of accumulation", occurs below the O, A, and/or E horizons, if present. The B horizon receives deposits of **illuviated** materials such as clay particles, Fe and Al oxides, humus (organic matter formed from the decay of plant and animal matter), carbonates, gypsum, and silicates leached from the overlying horizons. The common presence of Fe and Al oxide coatings often give the B horizon a redder or darker color than the adjacent horizons.

The **C horizon** is the soil layer that generally sees little influence from pedogenic weathering processes and is therefore comprised of partially weathered parent material. The C horizon represents a transition between soil and bedrock. As the upper portion of the C horizon undergoes weathering, it may eventually become part of the overlaying horizons. There is an obvious shift in soil structure between strongly developed B and C horizons that aids in identifying the horizon boundary in the field; however, the structure shift may be more subtle in weakly developed soils.

Under the C horizon comes the **R horizon**, or bedrock. Depending on the geographic location, environmental conditions, and landscape position, bedrock may be found in excess of 100 feet deep or merely centimeters from the soil surface. Bedrock is a consolidated layer of rock material that gave way to the soil properties found on the site. Bedrock is occasionally disrupted or broken up by tree roots, but roots generally cannot cause enough stress on the rock to fracture it, so much of the deeper bedrock weathering is biochemical in nature. The layer of freshly weathered material, in contrast to the solid rock (i.e., bedrock), is generally termed saprolite/saprock.

The division of the soil profile termed the **regolith** is defined as "the unconsolidated mantle of weathered rock and soil material on the Earth's surface which extends from the soil surface to the bottom of the parent material" (SSSA 2008). So basically, the regolith is the heterogeneous material that lies on top of solid rock. The soil **solum** is the weathered soil material in the upper soil horizons (typically A, E, and B horizons) located above the parent material (C horizon). Not every soil profile is comprised of the same horizons. Some profiles will contain O, A, E, B, C, and R horizons while another soil profile may only be composed of a C and R horizon. These differences in horizonation are what make soils unique. The unique characteristics of soil allow soil scientists to classify soils into different categories via Soil Taxonomy (see Soil Classification section).

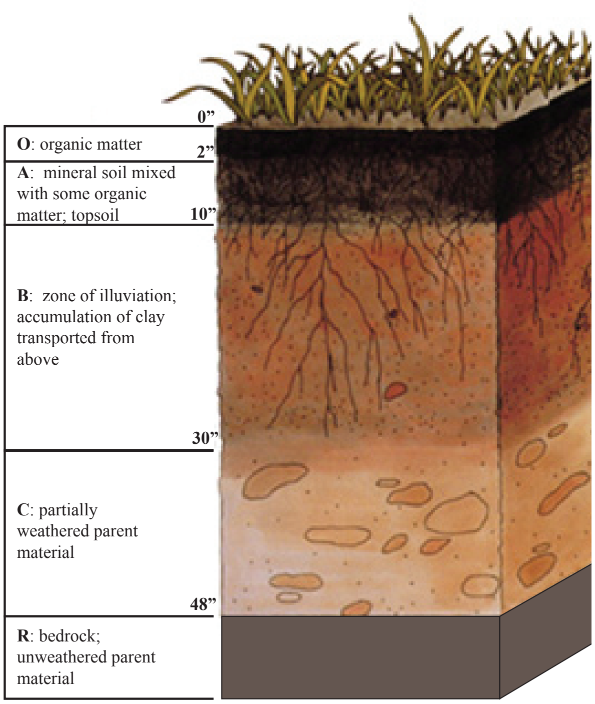


Figure 1. Master horizons identified in a typical soil profile. Source: USDA NRCS; adapted.

Soil Formation

The 5 soil-forming factors that influence the development of soil were first termed by Hans Jenny, an American soil pedologist in the early- to mid-1900s. The factors he determined as essential in the formation of soil include: parent material, climate, biota, topography, and time (Jenny 1994). Hans presented these factors as a formula: s = f (PM, Cl, O, R, T). The formula roughly translates to soil is a function of parent material, climate, organisms, relief, and time. This section will briefly discuss the role of each of the soil-forming factors and how each factor aids in soil development.

Parent material. Parent material is the unconsolidated and chemically-weathered mineral or organic matter from which the soil is developed. It consists of any number of combinations such as limestone, sandstone, or even volcanic rock. The area of the soil profile known as the "C Horizon" is comprised of parent material. Parent materials attribute to both the chemical and physical properties of a soil and can affect soil drainage, porosity, and plant available water, among other things. Parent material in any location can vary greatly even in areas adjacent to one another. For instance, Illinois contains eight different soil regions that are a result of glaciations, wind-blown materials, and continuous weathering of parent material.

Climate. In early soil profile development, parent material gives way to the major physical and chemical properties of a soil. As the soil becomes more developed (through horizon formation and increased soil structure over time), its characteristics depend more heavily on the climatic conditions to which it is exposed. Climate plays a significant role in the formation of soil and any number of climate-related occurrences (e.g., precipitation and temperature) may influence soil development.

Biota. Soil profile features related to biotic (plant and animal) activity such as burrows, mounds, root channels, and worm castings contribute to soil profile development because each of these processes change the porosity of the soil. The burrowing of animals, much like old root channels, creates large pores for rapid movement of water, gases, and solutes through the soil. The structure of some surface horizons is formed entirely by animal activity (earthworms, ants, termites, and other organisms). Earthworms are capable of consuming their own body weight in food daily (Minnich 1977). They are also responsible for the 'sinking' of objects through the soil profile over time (Darwin 1897). Charles Darwin devoted his last book, "The Formation of Vegetable Mould Through the Action of Worms" to the process of **bioturbation**, the process in which plants and animals facilitate the mixing, or rearrangement, of the soil profile.

Much like animals, plants can have a strong influence on soil properties. For example, whether a soil is formed under forest cover or prairie vegetation can greatly influence the carbon inputs into the system and ultimately how the soil is classified (see Soil Classification section). Plant roots increase infiltration, break up dense soil layers, and can pull nutrients and moisture from deep within the soil profile. Further, windthrow (uprooting of trees by wind) can create a pit and mound topography that helps physically weather the soil by dislodging and breaking rock. Windthrow can also expose deeper soils to surface conditions that may lead to accelerated chemical weathering.

Topography. Topography (slope and aspect) also has a strong influence on soil characteristics. Slope can influence erosion and deposition along a hillslope (Figure 2). Steep soils are susceptible to accelerated erosion and generally have a shallower A horizon and overall less development. Conversely, soil development in flat areas is heavily influenced by soil drainage, where well-drained soils tend to have greater development compared to poorly drained soils. A flat, poorly-drained soil retains water, leaving the soil profile saturated, which slows soil profile development. In well-drained soils, E horizons can develop above a well-developed B horizon due to the eluviation (transport of materials via water) of clay from the upper soil horizons. Additionally, the aspect (or horizontal direction) on which a soil is formed affects profile development. South-facing slopes receive more intense solar radiation than north-facing slopes, which affects soil temperature and moisture conditions. In the Appalachians, south-facing slopes are dominated by coniferous species while north-facing slopes are dominated by hardwood species due to differences in microclimate. Furthermore, topographic position (i.e., summit, shoulder, backslope, and toeslope) influences the development of soils. Generally, summits are well-drained and have strong horizon development, whereas shoulder and backslopes

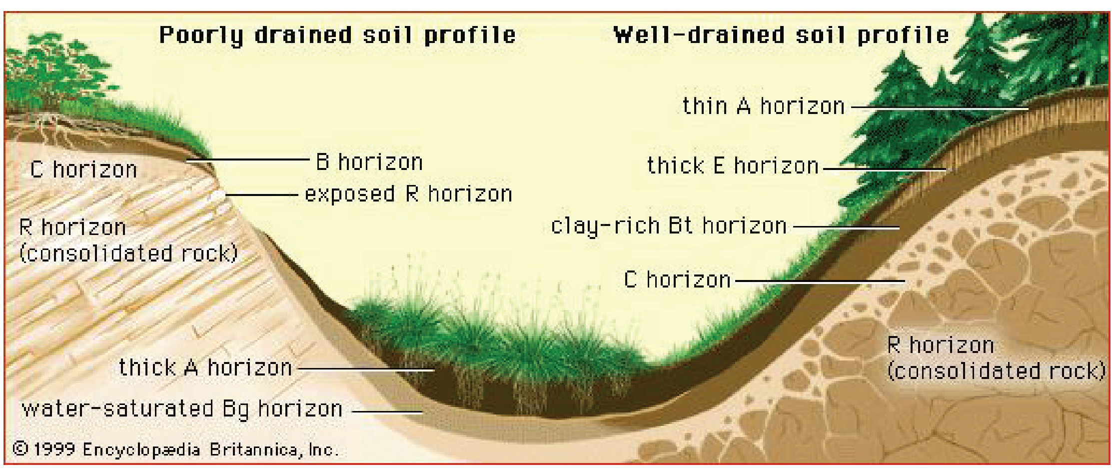


Figure 2. A comparison of hillslope soil profile development in poorly-drained and well-drained conditions. Surface erosion may occur in poorly-drained soils, exposing subsurface soils and transporting soil from upper horizons to the slope bottom. Source: http://www.britannica.com/EBchecked/media/19383/Soil-profiles-on-hillslopes-The-thickness-and-composition-of-soil (Encyclopedia Britannica, Inc. 1999) .

are influenced by erosion and have shallower topsoils and less infiltration. Toeslopes typically accumulate organic matter and topsoil from both alluvial (deposited by streams) and colluvial (primarily deposited by gravity) inputs, leading to thicker A-horizons overlaying relatively young soils.

Time. The duration of time a soil has undergone development is determined largely by the degree of weathering of the soil. Time has two separate meanings in terms of soil formation. Soil is influenced by both chronological and physiological time. The 'age' of a soil commonly refers to the degree or amount of weathering the soil has undergone. This age is not referring to chronological time, but the physiological characteristics attributed to the soil via the weathering process.

Soil Classification

Around the globe, many soil classifications systems have been developed to categorize soils into groups based on morphological and/or chemical properties. The most widely-used classification system is the Soil Taxonomy system that was made known by the United States Department of Agriculture (USDA) (Soil Survey Staff 1999). This system is a morphogenetic system that utilizes both quantitative factors and soil genesis themes and assumptions to guide soil groupings (Buol et al. 1997). "Keys to Soil Taxonomy", a free publication distributed by the USDA, is a great resource for in-depth classification of soils (Soil Survey Staff 2014a). The USDA has also published a free resource titled "Illustrated Guide to Soil Taxonomy" that is similar to "Keys of Soil Taxonomy", but written for a broader audience (Soil Survey Staff 2014b). Both resources can be found on the USDA website listed in the Soil Resources section of this article.

The Soil Taxonomy system is a hierarchical scheme consisting of 6 classification levels. In order from broadest to narrowest, the levels of classification are: 1) Order, 2) Suborder, 3) Great Group, 4) Subgroup, 5) Family, and 6) Series. Currently, there are 12 soil orders, 65 suborders, 344 great groups, ~ 18,000 subgroups, and over 23,000 soil series (Bockheim et al. 2014). The distribution of soil orders across the United States is shown in Figure 3. The defining characteristics of the broadest levels of classification are based on soil-forming processes and parent materials, whereas the narrower levels become much more specific and consider the arrangement of horizons, colors, textures, etc. The soil-forming factor "climate" has a predominate role in Soil Taxonomy classification, followed by parent material, and biota; topography and time are not utilized in defining taxa (Bockheim et al. 2014).

Soil Orders

Entisols are the 'youngest', or most recently formed soils of all the soil orders. Characteristics of Entisols include weak profile development where very little, if any, horizonation can be documented. Entisols sometimes contain a weakly formed A or Ap (plow layer) horizon. These soils can be found on steep slopes with severe erosion, on floodplains that receive alluvial deposits, and any number of scenarios in between.

Another soil order with notably weak profile characteristics is the **Inceptisol** order. When Soil Taxonomy was first established in 1975, Inceptisols were commonly referred to as the 'wastebasket soil order'. These soils generally did not fit into the other soil orders at the time. When additional soil orders were introduced, many Inceptisols were reclassified and the 'wastebasket' title no longer applies. Inceptisols are somewhere between the stages of no profile development and weak profile development. Inceptisols are commonly found along major rivers and streams due to the weak profile development. Over time, both Entisols and Inceptisols have the potential to develop more horizons, at which time they would likely be reclassified into a different soil order. The features of 'young' soils like Entisols and Inceptisols are more heavily influenced by their parent material, whereas 'old' soils are more influenced by climate and vegetation factors.

Gelisols are also 'young' soils in regard to geologic time and were developed under cold temperatures or frozen conditions. These soils are often associated with permafrost conditions and cryoturbation (frost churning) in places like Canada and Alaska. Permafrost is a perennially frozen soil horizon (SSSA 2008).

Mollisols are commonly referred to as the 'prairie soil'. These soils were formed primarily under grassy prairies and are characterized by their high organic matter content, dark color, and deep A horizon. The A horizon must be greater than 8 inches in depth and requires at least a 50 % base saturation (at least 50 % of the cation exchange sites are occupied; see Soil Chemistry section for more information). Mollisols are common in the midwestern United States where native prairies once dominated the landscape.

Alfisols, formed under deciduous forests, are also very common in the midwestern United States. Alfisols are generally found in humid regions of the world and often contain an E horizon in the soil profile. These soils must have a base saturation of at least 35 %.

Spodosols generally originate from coarse-textured (i.e., increased sand content), acidic parent materials. Spodosols are formed under forest vegetation, especially coniferous forests due to the buildup of pine needles that inherently have high acidic resins. When pine litter decomposes, strongly acidic compounds are leached through the coarse materials, transporting Fe, Al, and humus (Brady and Weil 2007). Thus, an illuvial layer of humus and Fe/Al oxides form. Like the Alfisols, an E horizon is commonly found in Spodosol soil profiles. In many cases, a Spodosol will have a white E horizon on top of a bright red B horizon. Spodosols are associated with loamy or sandy soil conditions and can be found in Wisconsin, Michigan, the northeastern United States, and on the coastal plains of the eastern and southeastern United States.

Aridisols are commonly associated with semi-arid and arid regions. These regions have a low mean annual rainfall. The lack of moisture in the soil affects the soil development and weathering process. Therefore, these soils are primarily affected by physical weathering, not chemical weathering (weathering processes discussed in the Soil Chemistry section). Aridisols are characterized by a high base saturation percentage of ~ 100 %. These soils can be found throughout the deserts or drier areas of the western United States.

Ultisols can be found in humid and warm regions such as the southeastern United States. Ultisols have a high amount of clay mineral

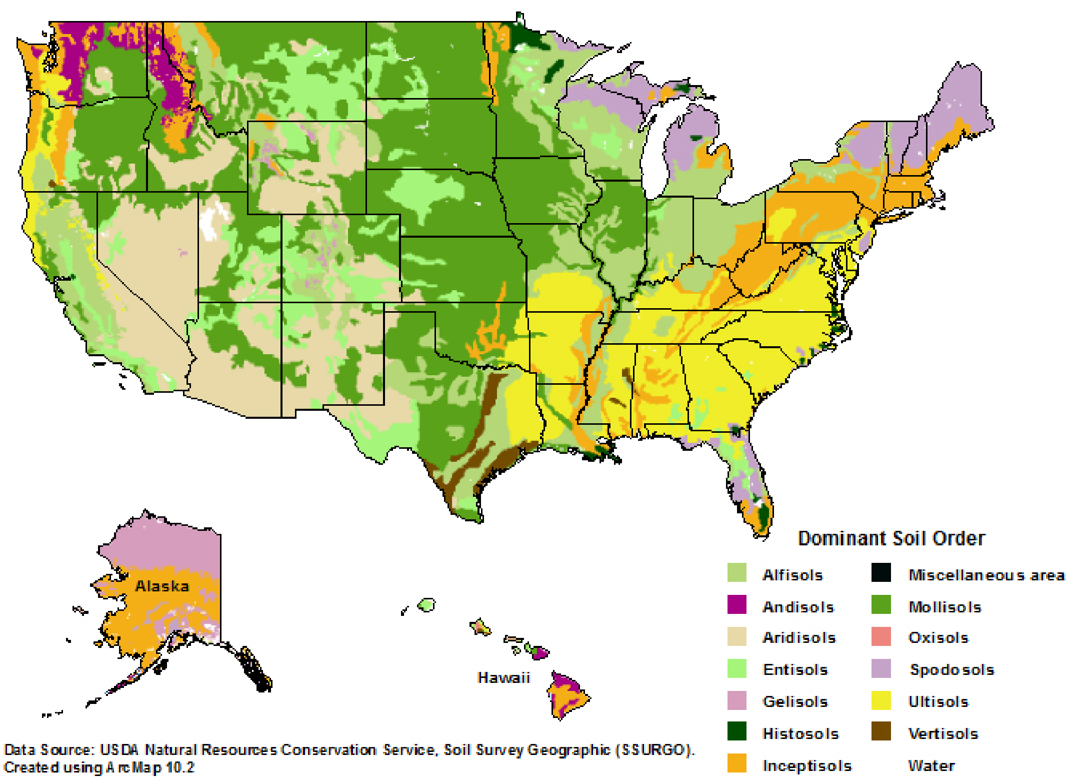


Figure 3. Distribution of soil orders across the United States.

weathering and translocation that leads to a subsurface accumulation of clays (Brady and Weil 2007). They have a base saturation of < 35 % and are naturally less fertile than Alfisols or Mollisols. However, Ultisols respond favorably to nutrient management and are cultivated in many regions of the world. These soils are characterized by a high degree of weathering and are typically more acidic than Alfisols, but less acidic than Spodosols.

Oxisols are the most highly weathered soil order in the U.S. classification system. Oxisols get their name from being oxidized. They are dominated by high clay content and Fe/Al hydrous oxides that typically give the soil a red hue. Oxisols can be found in tropical and sub-tropical regions of the world such as Hawaii, Puerto Rico, South America and Africa. Oxisols are generally formed in wetter environments, but can be found in areas that are presently drier than during the time the soils were formed (Brady and Weil 2007).

Vertisols are soils that lack profile development due to the expansion and contraction of clay-rich soil. These processes cause the soil to mix, which does not allow for clear soil profile development. During dry conditions, the soil shrinks and cracks form that can extend to ~ 80 cm deep and 2 to 3 cm wide. Vertisols are found in the southern United States in places like southeast Texas and eastern Mississippi where smectite, montmorillonite, and vermiculite clays are present.

The **Andisol** order was developed in 1990. Previously, these soils were grouped with the Inceptisol order. Andisols are soils of recent origin (young) that are developed from volcanic materials. They are found in Hawaii and the northwestern United States in places like Washington, Idaho, and Oregon.

Histosols are the only organic soil order in the classification system. Histosols are comprised of several different subhorizons within the O horizon and contain at least 20 % organic matter. Histosols occupy a small total area, but are found in various places in the United States and Canada such as Wisconsin, Minnesota, the Florida Everglades, and along the Gulf Coast.

Suborder, Great Group, Subgroup, Family, and Series

Suborders categorize properties associated with a climatic connotation of the soil. **Great groups** account for the most significant properties of the soil as a whole, including the type and arrangement of soil horizons, temperature regimes, and moisture regimes. Scientists use **subgroups** to further classify soils by assessing the degree of similarity between particular soils and grouping them accordingly. These are intergrades that reflect transitions to other orders, suborders, or great groups. The **family** grouping has similar physical, chemical, and mineralogical properties, which often relate to plant growth. A **soil series** is the lowest level of taxonomy, or the most specific to the soil in question. The soil series classification narrows characteristics of similar soils down to a local level where not only physical, chemical, and mineralogical properties matter, but also management, land-use history, vegetation, topography, and landscape position. Most soil series are named based on the location where the series was first discovered. An example of the taxonomic classification for the Illinois state soil is provided (Table 1).

Pedologists (scientists who study the origin and composition of soils as a component of natural systems) continue to learn more about soil morphology, chemistry, mineralogy, and biota, thus tighter limits on groupings of soils are being defined. Soil scientists are constantly reevaluating soil taxonomy as technology and

Table 1. Example of the taxonomic classification according to U.S. Taxonomy for the state soil of Illinois, USA.

Taxonomic Level	Example for IL State Soil
Order	Mollisol
Suborder	aquoll
Great Group	Endoaquoll
Subgroup	Typic Endoaquoll
Family	Fine-silty, mixed, superactive, mesic Typic Endoaquoll
Series	Drummer

science progress. It is important to remember that soils are dynamic, living environments. Soils are ever-changing through both chemical and physical weathering processes and can vary across the landscape, resulting in corresponding changes in soil classification over time.

Soil Physical Properties

In this section, soil physical properties will be introduced, examples for measurement will be provided, and the applicability in the field will be discussed. Soil physical properties have a profound effect on how soils influence soil quality and productivity. Oftentimes soil quality is driven by soil physical properties that determine nutrient and moisture levels in soils. The physical properties of soil include soil texture, bulk density, water holding capacity, organic matter content, soil structure, soil color, and soil consistence. A useful field guide for describing soil properties is "Field book for describing and sampling soils" (Schoeneberger et al. 2012).

Soil Texture

Soil texture is determined by the amount of sand, silt, and clay in a soil sample. Table 2 shows the size comparison of sand, silt, and clay particles based on the United States Department of Agriculture (USDA) System, one of the most commonly used among several particle size classification systems. Clays have a particle size diameter of < 0.002 mm, silts between 0.002 and 0.05 mm, and sands 0.05 to 2.0 mm. Percentages of sand, silt, and clay categorize soil into different textural classes. Particle size percentages can be compared to the USDA soil textural triangle (Figure 4) to determine soil texture. For instance, a soil with 18 % clay, 60 % sand, and 22 % silt would be considered a sandy loam. Soil texture can be determined in the lab via particle-size analysis using the hydrometer method; this method determines particle-size distribution by measuring the time it takes for soil particles in water to settle out of suspension. The hydrometer method can be time consuming, requires certain equipment, and is not optimal for most people. However, anyone can determine textural class using the "Feel" Method. This involves forming a moist soil sample into a ball and squeezing it between the thumb and index finger to make a ribbon. Texture is determined by ribbon length (if one can be formed at all) and grittiness or smoothness of the sample. A step-by-step guide to the "Feel" Method is available on the NRCS website (see Soil Resources section). With practice, the "Feel" Method provides an immediate and accurate way to determine textural class, and even percent sand, silt, or clay, while in the field. Laser Particle Size Analysis (LPSA) has become more commonly used in labs across the country. Although this method is accurate, it requires training/skill to use the analytical instrument and the initial cost is high.

Table 2. Particle diameter (mm) of sand, silt, and clay based on the United States Department of Agriculture System.

Texture Size Class	Particle Diameter (mm)
Very coarse sand (vcos)	1.0 - 2.0
Coarse sand (cos)	0.5 - 1.0
Medium sand (s)	0.25 - 0.5
Fine sand (fs)	0.1 - 0.25
Very fine sand (vfs)	0.05 - 0.1
Silt (si)	0.002 - 0.05
Clay (c)	< 0.002

Bulk Density

Bulk density is the mass of the soil in relation to a known volume of soil and is often used as an indicator of soil compaction. Soil compaction decreases the ability of a plant's roots to penetrate through the soil profile. Bulk density is related to soil textural class and soil porosity. Soils containing a high percentage of porosity will have a lower bulk density. Typically fine-textured soils have lower bulk densities than coarse-textured soils because of increased pore space both

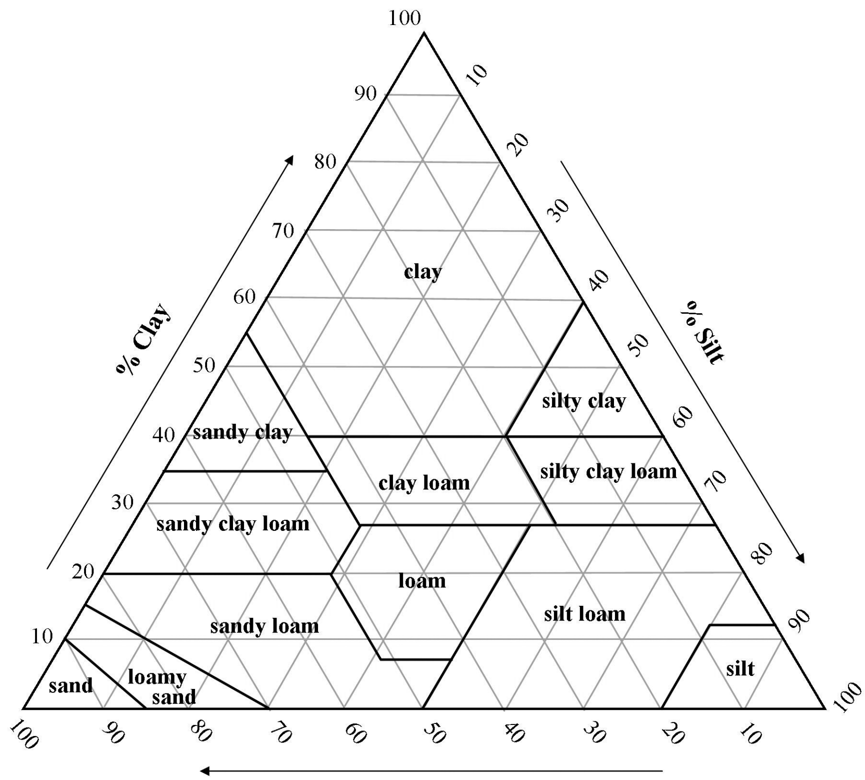


Figure 4. Soil textural triangle. Texture class is based on particle size percentages. Source: USDA NRCS soil textural triangle; adapted.

between (interstructural pores) and within (matrix pores) soil aggregates. Ideal bulk densities for plant growth range from < 1.10 g cm^{-3} for clays to < 1.6 g cm^{-3} for sands (Table 3). Bulk density is also affected by grain size and arrangement of coarse-textured soils. If sandy soils are loosely-packed and of uniform size, porosity is higher and therefore bulk density is lower than sandy soils with tightly-packed aggregates of different grain sizes. If a textural class has a bulk density reading that exceeds the growth-limiting factor for that class, then conditions for plant life are not optimal. Daddow and Warrington (1983) determined growth-limiting bulk densities according to particle size. Generally, the greater the clay percentage is within a soil, the lower the growth-limiting bulk density of the soil because of the increased pore space in clays. The growth-limiting bulk density is ~ 1.40 g cm^{-3} for soils with > 80 % clay and ~ 1.70 g cm^{-3} for soils with < 20 % clay (Daddow and Warrington 1983). The impact of bulk density on root growth according to textural class is shown in Table 3. In addition to texture, land cover and management also impact bulk density. Typically, bulk density readings in a forest are much lower than readings in an agricultural field or an urban area. Forest soils tend to have a higher amount of porosity because of tree rooting, increased biotic activity, increased organic matter on the soil surface, and less anthropogenic disturbances. Bulk density readings, soil texture data, infiltration capacity readings, and penetration resistance data can be compiled to explain soil porosity or degree of compaction. Compaction affects both root penetration and the soil's ability to allow precipitation to infiltrate into the soil profile. Bulk density is commonly measured using a core method where a known volume of soil is collected with a cylindrical soil core, then oven-dried, and weighed. Results are reported as a mass per unit volume (e.g., g cm^{-3}). Bulk density can also be determined via the clod method, where a clod (or ped) of soil is coated in paraffin wax and placed in water to determine the exact volume based on displacement. The clod is then oven-dried,

Table 3. Relationship between bulk density and root growth based on soil texture. Source: Arshad et al. 1996.

Textural class	**Ideal bulk density ($g\ cm^{-3}$)**	**Bulk density that may affect root growth ($g\ cm^{-3}$)**	**Bulk density that restricts root growth ($g\ cm^{-3}$)**
Sands, loamy sands	< 1.60	1.69	> 1.80
Sandy loams, loams	< 1.40	1.63	> 1.80
Sandy clay loams, clay loams	< 1.40	1.60	> 1.75
Silts, silt loams	< 1.30	1.60	> 1.75
Silt loams, silty clay loams	< 1.40	1.55	> 1.65
Sandy clays, silty clays, some clay loams (35 - 45 % clay)	< 1.10	1.49	> 1.58
Clays (> 45 % clay)	< 1.10	1.39	> 1.47

weighed, and reported on a mass/volume basis like the core method. 3-D scanners are also used to determine accurate clod volumes.

Water Holding Capacity

Water holding capacity is the amount of water held by soil. The water holding capacity of a soil is reliant on soil texture, structure, organic matter content, and arrangement of soil pores. Organic matter has a high degree of microporosity, which allows it to retain more water. Therefore, soils with a higher amount of organic matter and/or a large percentage of micropores (e.g., fine-textured soils like clays) generally have a higher water holding capacity. Soil compaction also impacts water holding capacity since soil compaction weakens soil structure and collapses pores, thereby decreasing the soil's ability to hold water. There are several different terms used to discuss water capacity in soils. **Available water** is the amount of water that is readily available for plant uptake; conversely, unavailable water is water that plants cannot utilize. **Gravitational water** (water that drains freely until field capacity is reached) is a form of unavailable water. **Field capacity** refers to the water held by the soil following 24 to 48 hours of free drainage and is available for plant uptake. The **permanent wilting point** is the point at which plants wilt and are unable to recover due to a lack of plant available water. Lastly, **saturation** occurs when all pores are filled with water (Figure 5).

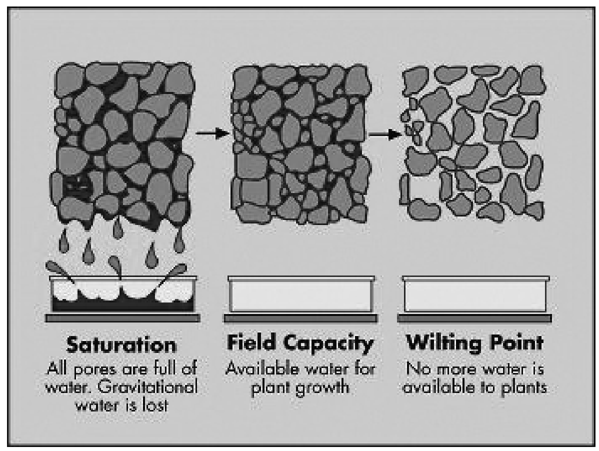


Figure 5. Water holding capacity stages within the soil. Source: Department of Agriculture Bulletin 462, 1960.

Soil Structure

Soil structure is the description of how individual soil particles (sand, silt, and clay) are arranged into soil **aggregates** (also called **peds**) and reflects both physical and chemical weathering. Several factors influence soil structure, including soil texture, soil moisture, organic matter content, compaction, the activity of soil organisms, and management practices. Soil structure is easiest to observe in dry soil. When characterizing soil structure, the shape, size, and grade of the structural units (peds) are defined. The primary soil structure shapes are granular, platy, blocky, prismatic, and columnar. **Granular** soil structure contains peds that are generally small and round and are commonly found in horizons near the surface where high amounts of root activity are present and porosity is greater. **Platy** soil structure consists of peds that are plate-like (flat and thin) and usually oriented horizontally. Platy soil structure may occur throughout the soil profile, but is common in E horizons or compacted soil. **Blocky** soil structure consists of sharp-edged peds arranged in square or angular blocks and is typically found in the subsoil, especially in humid regions. **Prismatic** soil structure contains peds that are longer vertically than horizontally and have flat tops. **Columnar** soil structure is similar to prismatic, but peds have distinct rounded tops. Both prismatic and columnar soil structure are commonly found in the subsoil of arid and semi-arid regions. Soils can also be defined as "structureless" where soil structure is **single-grained** (typically sand particles that do not stick together) or **massive** (aggregation is not present). Aggregate **size** is typically described as very fine, fine, medium, coarse, or very coarse and the size limits of these classes depend on the aggregate shape. **Grade** describes the distinctness of the peds and is classified as weak, moderate, or strong. More information on size and grade can be found in the Soil Survey Manual (Soil Survey Division Staff 1993). A soil structure description is written as "grade, size, shape", such as "moderate medium subangular blocky structure." Soil structure greatly impacts soil porosity, thereby influencing soil water movement. General infiltration rates (rapid to slow) associated with soil structure shapes are shown in Figure 6.

Soil Consistence

Soil consistence is a measure of the response of soil to applied pressure at various moisture contents. In other words, how well does the soil hold together when under applied stress? Soil consistence is measured separately for dry, moist, and wet soil because moisture content impacts how a soil responds to pressure. In the field, soil consistence is measured by testing the ease with which the soil is crushed between the thumb and forefinger, or underfoot. Additionally, the terms stickiness and plasticity are often used to describe wet consistence. **Stickiness** refers to how well wet soil adheres to other objects (like your fingers) after pressure is released, while **plasticity** describes the malleability of wet soil. Further reading on the topic, including the scale used to describe consistence at different moisture contents, can be found in chapter 3 of the Soil Survey Manual (Soil Survey Division Staff 1993). Soil consistence is one of many soil physical properties used to determine site suitability for agriculture or engineering purposes.

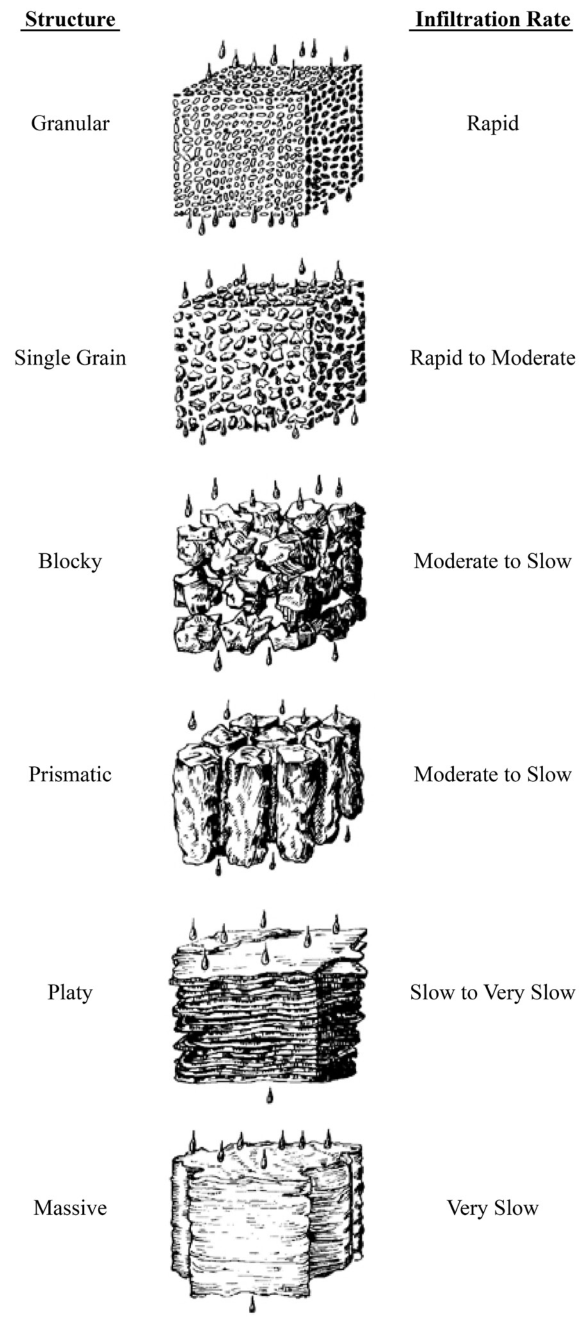


Figure 6. Water infiltration rates associated with typical soil structure shapes. Source: USDA; adapted.

Soil Color

Soil color is important in determining soil classification. The **Munsell color chart**, a book containing standard color chips similar to paint chips found at a hardware store, was developed as the standard system for determining soil color. Color is determined from three characteristics: hue, value, and chroma. **Hue** refers to the degree of redness or yellowness of soil. **Value** refers to the lightness or darkness of soil. **Chroma** refers to the brightness or dullness of soil. A freshly exposed face or ped is used to determine color. Using moist soil is most common and dry soil may be misted with water. In direct sunlight, the moist soil ped is compared to the Munsell color chart to determine the hue, value, and chroma. Soil color varies with topography, climatic factors, and soil depth, among other variables. Drainage characteristics of a soil can have a large impact on soil color; thus, soil color can reveal insights into the local hydrologic regime. Soils that are well-drained tend to be brighter than poorly-drained soils. Poorly-drained soils create anaerobic conditions in which the Fe in the soil is reduced, resulting in very dull colors. Soils with extremely reduced conditions and a chroma < 2 are referred to as "gleyed" soils.

Organic Matter

Organic matter content has a profound influence on both soil processes and soil quality. In the field, high organic content may be recognized by a dark soil color in the surface horizons. In the lab, organic matter content is quantified by Loss on Ignition, a process in which a soil sample is exposed to high temperatures (360° C) and the amount of weight lost after exposure is assumed to be organic carbon. Organic matter in soils promotes biotic growth since it serves as a food source for earthworms and other organisms. Organic matter has a high water infiltration capacity, a high moisture holding capacity (it can hold between 80 and 90 % of its weight in water), and contains many plant-essential nutrients. The increased water holding capacity allows more water to be available to plants over a longer timeframe. Along with aiding in the retention of soil moisture, organic matter protects the soil against the kinetic energy of raindrops and also acts as an insulation layer for the soil surface. Without organic matter, bare mineral soil is much more susceptible to accelerated erosion processes. Since billons of tons of soil in the world are displaced every year, it is important for soil organic matter to remain intact whenever possible. Additionally, organic matter acts as a binding agent for nutrients and potential contaminants, and therefore aids in reducing inputs of these contaminants to waterbodies. Depending on environmental conditions, organic matter can be stored in the soil for long periods of time. Warm, humid conditions promote breakdown of organic matter by microorganisms, whereas cooler, drier climates limit decomposition and soils act as a carbon reservoir. Tillage also impacts organic matter storage in agricultural soils. Tillage generally reduces organic matter content, as it improves conditions for decomposition by increasing pore space and moisture content and by exposing organic matter adsorbed to soil aggregates; converting to no-till agriculture has been shown to increase organic matter content in soils (Schlesinger and Andrews 2000).

Soil Water Movement

Soil water is the amount of water present in the **vadose zone**, or the zone of unsaturated flow, of the soil profile. The term **groundwater** refers to the area of saturated flow in the soil. Water enters the soil profile through the process of **infiltration**, and then moves through the soil profile via **percolation**. These processes depend on various soil properties that range from soil porosity to the shape and arrangement of soil peds (Figure 7). Water moves through the available pore space more readily and at a faster rate in soils with granular structure when compared to the longer flow path that platy soil structure provides (Figure 7). The percentages of micropores, mesopores, and macropores in the soil horizons also influence how quickly water enters into and moves through the soil profile. **Micropores**, or capillary pores, are the smallest soil pores and contain most of the plant-available water in soil. Water is held in these pores by the combined matric forces of adhesion and cohesion. **Adhesion** is the ability of a water molecule to adhere to a soil particle. **Cohesion** is the ability of a water molecule to stick to itself (or other water molecules). **Mesopores** are medium-sized pores formed by numerous processes like

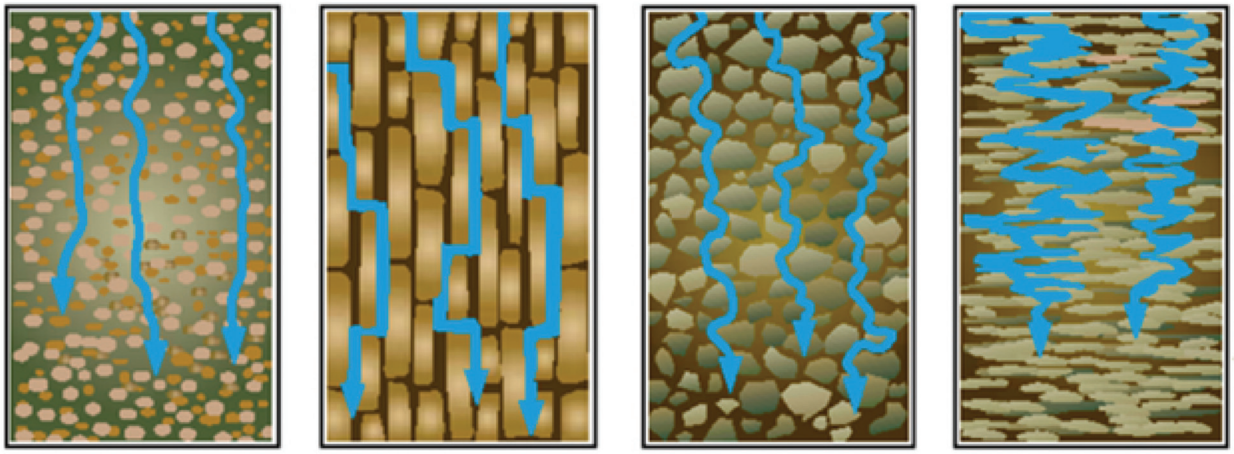


Figure 7. Water movement through soils with differing soil structure. Source: USDA NRCS, adapted.

the shrinking and swelling of clays, earthworm activity, and freeze-thaw cycles. These pores are primarily drained during the period of free drainage (gravity-driven drainage immediately following a rain event), although some water drained by mesopores is eventually plant available if the drainage network leads into micropore spaces. **Macropores** are the largest of the soil pore classification. Some macropores are formed by the burrowing of animals (**non-matrix pores**) while others exist because tree roots that once occupied the soil have rotted away. Drainage in macropores is gravity-driven and rapid. The water in these pores is quickly replaced by air; therefore, macropores cannot supply plants with needed water. Soils containing a range of pore sizes will have good drainage and air available to plants (from large pores), in addition to water plants can access (from small pores). Ideal pore distribution is generally found in a well-structured soil with the majority of small pores within soil aggregates (**matrix pores**) and large pores between soil aggregates (**interstructural pores**) (Kimmins 1997). Forest soils contain a larger percentage of organic matter that results in better soil aggregation and porosity; thus, moisture availability in forests is usually greater than in agricultural or urban environments.

Soil Water Potential

Soil water potential is the measure of the energy status of the soil water and reflects the amount of water available for plant uptake. Water moves from areas of high energy to areas of low energy within the soil.

Soil water has three types of energy: gravitational, matric, and osmotic. **Gravitational potential** refers to the energy related to the elevation of water within the soil; water at the soil surface has a high gravitational potential, but once it reaches the water table the gravitational potential is zero. **Matric potential** is the energy associated with adhesion and cohesion within the soil matrix (or profile) and is a negative potential since it opposes gravitational and osmotic potential. **Osmotic potential** measures dissolved chemicals within the soil; the higher the concentration of dissolved chemicals, the less room water has to move, though typically this has little contribution to overall soil water movement except in saline soils. Soil water potential is presented as the following simplified formula:

$$\Psi_T = \Psi_G + \Psi_M + \Psi_O$$

where Ψ_T is total soil water potential, Ψ_G is gravitational potential, Ψ_M is matric potential, and Ψ_O is osmotic potential. This energy status reflects the amount of energy required to extract water from the soil.

Soil water potential is typically measured in bars or kilopascals of pressure. It is important to note that soil water potentials in the vadose zone are recorded as negative pressures. Positive pressure values would indicate that the soil is saturated and when this occurs, it means that the water being evaluated is not true vadose zone soil water since the vadose zone is unsaturated. The most common device used for measuring soil water potential in the field is a water-filled tube called a tensiometer. Water flows from a higher potential (inside the tube) to a lower potential (within the soil matrix) until an equilibrium is reached and the soil water potential is displayed as a negative value (range of 0 to -85 kPa) on the tensiometer vacuum gage. The closer the value is to 0, the closer the soil is to saturation. Smaller values (closer to -85 kPa on the negative scale) mean drier soil and that more energy is required to extract water.

Texture and structure may vary from one horizon to another, which can influence the movement of water through the soil profile. Soil texture affects how water moves through the soil and how much water can be stored in the soil. Soil structure affects the ability of roots to penetrate the soil, the amount of water a plant can uptake, and water movement through the soil. A poorly structured soil may have as little as 35 % total porosity, while a well-structured soil of the same texture may have 65 % total porosity (Kimmins 1997). A well-structured soil will be more efficient at soil water movement and plant uptake. Additionally, because small pores have more matric potential (adhesion and cohesion forces) than large pores, fine-textured soils that contain more micropores generally hold more water than coarse-textured soils containing a greater percentage of macropores. By the time **field capacity** (**FC**) (soil is not saturated, but wet) is reached, most of the gravitational water is lost, larger pores become filled with air, and water is held within smaller pores. At FC, most water is plant available and soil water potential values typically show ~ -10 to -30 kPa (Brady and Weil 2000). The **permanent wilting point** (**PWP**) is the potential at which soil water is unavailable for plant uptake (~ -1500 kPa). At PWP, plants cannot recover from water stress and will remain wilted. However, there is still a small amount of hygroscopic water in the smallest pores. The **available water content** (**AWC**) is considered to be the soil water retained between FC and PWP and is presented as the formula:

$$AWC = FC - PWP.$$

From this formula, the t**otal available water content** (**TAW**) can be obtained by multiplying the AWC by the depth of the plant root zone (Rd) or:

$$TAW = AWC * Rd.$$

Soil Chemistry and Plant Uptake

Soil chemistry plays a key role in vegetative productivity and species composition and is largely determined by weathering of rock, rock type, the cation exchange capacity of the soil, acid production resulting from microbial and root respiration, and management strategies of the soil. The soil provides nutrients necessary for plant growth. The sources of plant nutrients range from biogeochemical cycling inputs, decaying organic matter, amendments added by humans (e.g., fertilizers and pesticides), and nutrients naturally occurring within mineral soil.

Weathering

There are two processes associated with soil weathering: physical and chemical weathering. **Physical weathering** is the establishment of sufficient stress on a rock so that it *physically* breaks the rock. Mechanisms that fall within the category of physical weathering include erosion, freeze-thaw cycles, bioturbation (plants and animals physically disturb the soil and plant roots may physically crack rock apart), and formation of cracks or gaps in soils. Parent material weathers to release primary minerals to soils. **Chemical weathering** is defined as a change in the chemical nature of rock, resulting in a change in mineral structure, reactivity, surface area, and particle size; it is driven by the instability of primary minerals at the earth's surface. The minerals must be exposed to the environment for weathering to take place. Primary minerals include quartz, feldspars, muscovite, and biotite. These minerals have persisted through geologic time and their mineral composition shows only negligible differences from their original state. Chemical weathering is generally responsible for the formation of secondary minerals, which are derivatives of primary minerals. Secondary minerals are the fine materials that make up clay particles in the soil. The presence of clay in a soil signifies an active history of weathering. An example of a primary mineral weathering to form a secondary mineral is the breakdown of feldspar (primary) into clay (secondary). Chemical weathering reactions increase in warm, humid climates and are also enhanced by the presence of water and oxygen, as well as biological agents including the acids produced by microbial and plant-root metabolism (Brady and Weil 2007).

The four primary chemical weathering processes are oxidation, reduction, hydration, and hydrolysis. **Oxidation** occurs when the oxygen supply is high and an element loses electrons; an example is when ferrous Fe combines with oxygen to form ferric Fe oxide (or rust). **Reduction** occurs when an element gains electrons and generally occurs in anoxic (oxygen-depleted) environments. **Hydration** is a result of the association of water molecules onto the mineral structure (e.g., anhydrite and water forms gypsum). Lastly, **hydrolysis** is essentially an attack on the silicate structure by hydrogen ions, meaning water breaks down the rock. Chemical weathering weakens the rock structure and makes it more susceptible to additional weathering.

Cation Exchange Capacity

Clay and organic matter have what is referred to as **cation exchange capacity** (**CEC**), which is the total sum of exchangeable cations that a soil can adsorb. Clay and organic matter are negatively charged, thereby possessing the ability to adsorb and hold cations (positively charged ions) onto what is known as the cation exchange complex. Cations, such as K^+, Na^+, and Ca^{2+}, can be adsorbed onto soil or organic **colloids** (very small chemically reactive particles with a large surface area per unit mass), making the cations available for plant uptake by preventing cation leaching from the system (Brady and Weil 2007). Soils high in organic matter and/or clay generally have a greater CEC than soils with little humus or clay (i.e., sandy soils), though CEC can vary greatly depending upon the type of clay and amount of organic matter present. CEC must be measured in a lab.

Soil pH

Soil pH is a measure of the hydronium ion in the soil solution, which determines the acidity or alkalinity of the soil. Soil pH varies by region and acidic soils are typically found in wet climates, whereas alkaline soils are generally found in areas with limited rainfall. Soils may become acidic through the weathering of rocks rich in silica, production of acids from organisms, and through the release of acids from decaying organic material. Alkaline soils are a result of the weathering of rocks such as limestone that contain large amounts of calcium carbonate (salts) and from the dust inputs of salts resulting from the evaporation of drainage basins, primarily in arid regions. Soil pH affects nutrient solubility and decomposition rates in soil and thereby has a profound effect on the availability of nutrients to plants. A slightly acidic pH of between 6 and 7 appears to provide optimal nutrient availability to plants, though there are exceptions (Kimmins 1997). Most macronutrients are available within this range. Knowledge of the soil pH profile is especially important in making crop management decisions as some plants may require a set pH range for optimal growth. Soil pH can be measured in the lab using a pH meter or in the field with quick test strips.

Nutrients

There are a number of essential elements required for plant growth that are categorized as macronutrients or micronutrients. The difference lies in the quantities needed for plant growth. **Macronutrients** are elements that are needed in greater quantities, whereas **micronutrients** are required in smaller portions. All are required in varying quantities for optimal growth. Macronutrients include nitrogen (N), potassium (K), calcium (Ca), magnesium (Mg), phosphorus (P), and sulfur (S). Micronutrients include chlorine (Cl), iron (Fe), boron (B), manganese (Mn), zinc (Zn), copper (Cu), molybdenum (Mo), cobalt (Co) and nickel (Ni). Macronutrients can further be classified into primary and secondary nutrients. Generally N, P, and K are considered primary nutrients because they are most often the nutrients limiting plant growth. Ca, Mg, and S are rarely limiting nutrients and as such are considered secondary nutrients. Primary nutrients are discussed in greater detail below.

Nitrogen. Nitrogen is the nutrient needed in the greatest quantities by plants and is generally one of the most limiting to plant growth due to lack of environmental availability. The atmosphere contains a large reservoir of nitrogen gas (~79 %

of the atmosphere), most of which is unavailable to plants and animals. Both inorganic and organic forms of N are found in soils; however, only the inorganic form is available for plant uptake. Most of the soil N (> 95 %) exists in organic form and is therefore unavailable. Nitrate (NO_3^-) and ammonium (NH_4^+) ions are the two inorganic forms utilized by plants. Nitrate is held primarily in solution and is readily available for plant uptake. Ammonium ions are mostly held on the cation exchange complex. Fortunately, soil microbes can break down organic N (NH_2) and convert it to forms usable by plants (NH_4^+ and NO_3^-) in a process known as nitrogen mineralization. Immobilization of N can also occur when inorganic N is converted to unusable organic form.

Sources of N are primarily from the atmosphere, biological fixation, and fertilization. Biological fixation accounts for the majority of N inputs in most ecosystems (Kimmins 1997). In agricultural systems, annual biological N fixation is estimated at 50 - 70 million metric tons of N globally, primarily from the symbiotic relationship between leguminous crops (dominated by soybeans) and rhizobia (nitrogen-fixing bacteria) (Herridge et al. 2008). Nitrogen deficiencies in plants are typically noticed by the yellowing of foliage and stunted growth. Because N deficiencies are widespread and can lead to poor crop yields, N is often applied in excess. Nitrate is extremely mobile and readily leached from the soil if not used by plants. High NO_3^- concentrations (> 10 mg L^{-1}) in drinking water are a danger to public and ecosystem health, thus nitrate in drinking water is regulated by the Environmental Protection Agency. Additionally, excess N in the soil can lead to incomplete denitrification, which generates nitrous oxide into the atmosphere. Nitrogen is a nutrient requiring careful management, critical for both successful crop production and environmental quality.

Phosphorus. Phosphorus is second only to nitrogen in the amount needed for optimal plant growth. The majority of soil P is derived from mineral weathering and organic matter decomposition, but concentrations of plant-available P are generally very low in soils. Most soil P is in insoluble forms that are unavailable to plants and when soluble forms of P are added via fertilization, they can be converted to insoluble forms over time. Decomposition returns P to the soil, but if crops are removed, the P is also removed from the system. For these reasons, P is often a limiting nutrient in the soil. Phosphorus deficiency in plants is recognized by bluish-green foliage, sparse flowering, and stunted, thin stems. Because plants require large quantities of P and there is little natural available P from weathering, crop harvesting removes the majority of P from the field. Without P amendments, the subsequent crop will likely be P deficient, which has led to the over-fertilization of fields and an accumulation of P in the soil. Unlike nitrate, which is mobile downward through the soil profile, P binds readily to sediment and is easily transported in this bounded state to streams and rivers. Excessive P in runoff can promote the **eutrophication** (over-abundance of algae growth caused by excessive nutrient accumulation) of downstream water bodies. The resulting algal growth decreases the dissolved oxygen levels in the water, which may lead to substantial fish kills. With the Mississippi River Watershed draining much of the nation's cropland, the Gulf of Mexico consistently has one of the largest dead zones in the world due to eutrophication; the average size of the dead zone over the last 5 years is ~ 5,500 mi^2. For this reason, P management in watersheds is of primary concern.

Potassium. Potassium is available in greater quantities than any other soil macronutrient and is essential in providing protection against crop disease. However, most of the K within the soil exists as a mineral and is not readily available for plant uptake. The K-containing minerals, such as feldspars and micas, are resistant to weathering; this leads to minimal K inputs from weathering during a growing season. Only ~ 2 % of soil K is readily available for plant uptake and is either in solution form or exchangeable form (Brady and Weil 2007). Potassium in the soil solution is immediately available to plants. Exchangeable K is a part of the cation exchange capacity of soils and is adsorbed on the soil colloid. The dissolved and exchangeable K concentrations are in equilibrium. For instance, when plants remove K from the soil solution, K is released from the cation exchange complex into the soil solution until K equilibrium is reached. Potassium also occurs in nonexchangeable or fixed form. Fixed

K is trapped between clay particles and remains unavailable until it converts to exchangeable K. This conversion usually does not occur within the span of one growing season; therefore, fixed K is considered a slowly available form of K.

Plants uptake large amounts of K in their aboveground biomass, often more than needed for growth. Because of this excessive uptake, harvesting crops or forests can remove large amounts of K from the system each year. Potassium deficiency is normally seen first on the lower plant leaves because K is translocated from older to younger tissue. Deficiency symptoms include yellow scorching along the leaf edge, slow growth, and weak stalks. Like nitrate, K is extremely mobile and readily lost via leaching. Applying substantial amounts of K fertilizer can lead to excessive plant uptake and loss to leaching. In addition to the soil itself as a natural K source, leaving crop residue on the soil can return a significant portion of K to the soil.

Role of Soil Biology

One critical function of soil is to provide a home for organisms. Soil biota plays an integral role in soil ecosystems by decomposing leaves, downed logs, and animals, and also providing the primary nutrient source for vegetation. Soil biota includes both flora (plants) and fauna (animals). Soil fauna subsists on a wide variety of energy sources, including: living plant material (herbivores), animals (carnivores), dead material (detritivores), fungi (fungivores), and bacteria (bacterivores). The size of soil fauna also varies. Macrofauna (> 2 mm) includes animals such as groundhogs, moles, earthworms, centipedes, ants, and termites; mesofauna (0.1 - 2.0 mm) includes springtails and mites; microfauna (< 0.1 mm) includes species such as rotifers, nematodes, and other single-celled organisms. Soil flora includes organisms as small as diatoms and algae up to the size of tree roots. An important member of soil flora is mycorrhizae, fungi that form a symbiotic (mutually beneficial) relationship with plant roots. Most plants contain roots infected with mycorrhizal fungi. Mycorrhizae enhance water and nutrient absorption by increasing root surface area and accelerate mineral weathering which releases nutrients to the soil (Fisher and Binkley 2000). Collectively, soil biota carries out enzymatic and physical processes that decompose organic matter, build soil humus, and make nutrients available for plants. Table 4 provides a description of the microfauna numbers found in a teaspoon of soil.

Decomposition is one of the most critical roles that soil biota play in an ecosystem. Without efficient decomposition, organic material would accumulate on the soil surface and nutrients would be bound within the material. Decomposition is initiated immediately when a leaf, twig, or fruit hits the ground. Once on the ground surface, biota begins to physically break down the material, creating more surface area to which flora can adhere.

Soils and Roots

Roots are a critical component in the soil environment. Plants rely on roots for structure,

Table 4. Brief description of the organisms in a teaspoon of soil. (Source: Melendrez 1975).

Organism	Number of Individuals per Teaspoon of Soil	Primary Role
Bacteria	5 to 500 million in agricultural soils; 20 million to 2 billion in forest soils	Consume readily decomposable materials
Fungi	Up to 40 miles of fungal hyphae	Consume hard to decompose organic matter
Protozoa	100 to 100,000	Feed on bacteria and each other
Nematodes	5 to 500 with high variability among soils	Feed on bacteria, fungi, and plant roots
Microarthropods	Several species	Feed on fungi, plants, and organic matter

support, water, and nutrient uptake. The relationship between roots and mycorrhizal fungi increases nutrient availability and absorption. Roots also act as a reservoir for food storage (starches) and sometimes synthesize growth hormones for the plant. Root growth is controlled by soil moisture, compaction, structure, texture, temperature, and chemistry. Once roots decay, the channels left behind improve air and water movement within the soil.

Nutrients are taken up by roots by the processes of root interception, mass flow, and diffusion. **Root interception** occurs when roots grow towards nutrients in nutrient-rich soil so that they can be utilized by the plant. Since the roots must continually grow in undepleted soil for root interception to occur, this process is limited. **Mass flow** occurs when nutrients are transported with soil water to a root that is actively extracting water from the soil. This process is most effective in periods of rapid transpiration with high concentrations of nutrients in the soil water solution. **Diffusion** occurs when nutrients move from high concentration areas (nutrient saturated) to low concentration areas (nutrient depleted) near the root surface. Rates of uptake via diffusion depend on concentration gradients, soil water contents, ion size and charge, soil temperature, and root adsorption rates. Water enters the root through root hairs or the cortex. Osmotic pressure (movement of water from areas of high to low concentration) causes the water to enter into the plant cell. The expansion and contraction of the roots cause water to move up through the cortex, through the xylem vessels, the stem, and into the rest of the plant. A manometer, an instrument used for measuring the pressure of a fluid, is used to measure the pressure of a root system. Root pressure is the pressure exerted on the liquid contents of cortical cells in roots. Cortical cells, which aid in the transport and storage of water and nutrients, are either turgid (expanded) or flaccid (contracted). Turgor pressure is the actual hydrostatic pressure developed inside a cell. This pressure is due to endosmosis, or the inward flow of water from outside of the cell. Flaccidity is when the cell undergoes exosmosis, the opposite of endosmosis, where water is lost and the cell becomes limp. To understand how root pressure works, cut a well-watered plant close to the ground, quickly attach a manometer to the stem and observe how the pressure changes on the gauge. The cut stem will exude water, suggesting pressure from the roots to the stem is being released. Although most water is absorbed through roots, some plants have developed the ability to absorb water through their leaves. Along the California coast, ~ 80 % of the redwood species, *Sequoia sempervirens*, absorb water deposited by fog through their leaves (Limm et al. 2009). This adaptation is especially useful in areas prone to drought, like California.

Plants have both primary roots and secondary roots (Figure 8), which come in many different shapes and sizes. Plant root networks are heterogeneous and no two root systems will be identical. Roots adapt and grow in response to environmental conditions. There are three common root systems of North American tree species (Figure 9). **Tap root** systems have a prominent tap root and smaller (secondary) lateral roots that grow off the side of the dominant primary root. Tap root systems are effective in areas where access to water is located deep within the soil profile so water can be accessed in periods of drought. Thus, many tree species with tap roots are well-adapted for upland and dry site conditions. **Heart root** systems occur in both upland and bottomland tree species and are adapted for mesic (moderately moist) site conditions. **Flat roots** are shallow root systems that often occur in bottomland species. Tree species with flat root systems are commonly uprooted in high windstorms when the ground is near saturation. Contrary to popular belief, ~ 90 to 95 % of tree roots are found within 1 m of the soil surface and most tree root systems extend out ~ 2 times the width of the crown. Absorption of nutrients occurs mainly in fine roots (< 2 mm in diameter) which are concentrated in the surface horizons (Kimmins 1997). Trees rely on these roots for access to water and nutrients. Root systems of various tree species are shown in Table 5.

Soil Erosion and Conservation

Soil erosion is a major concern around the globe. In order to properly prevent and manage erosion, it is important to understand erosion concepts. Soil erosion is both naturally-occurring

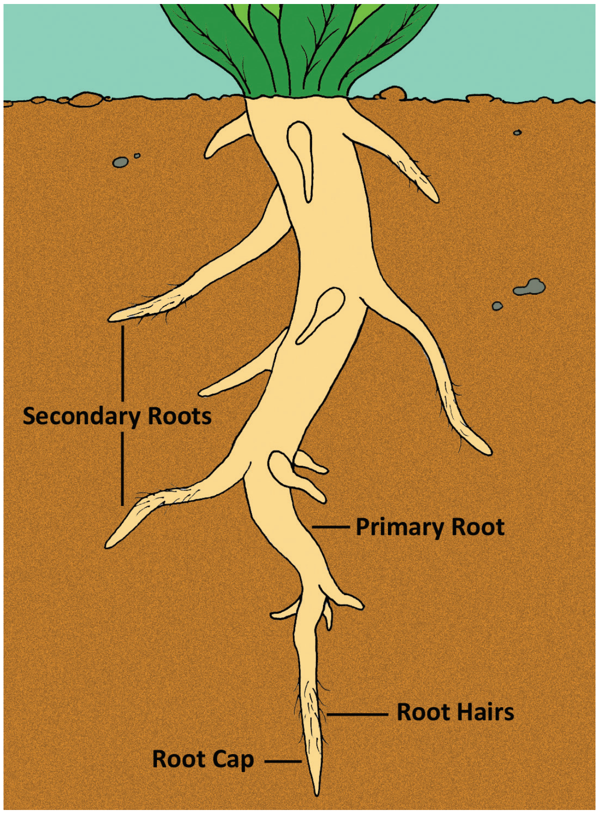


Figure 8. Common root system shapes for North American tree species. Drawing by Robin L Quinlivan.

Table 5. Common root systems for various tree species in the United States.

Tap root	**Heart Root**	**Flat root**
Hickory	Red Oak	Fir
White Oak	Honey Locust	Spruce
Butternut	Basswood	Sugar Maple
Walnut	Sycamore	Cottonwood
Hornbeam	Pine	Silver Maple

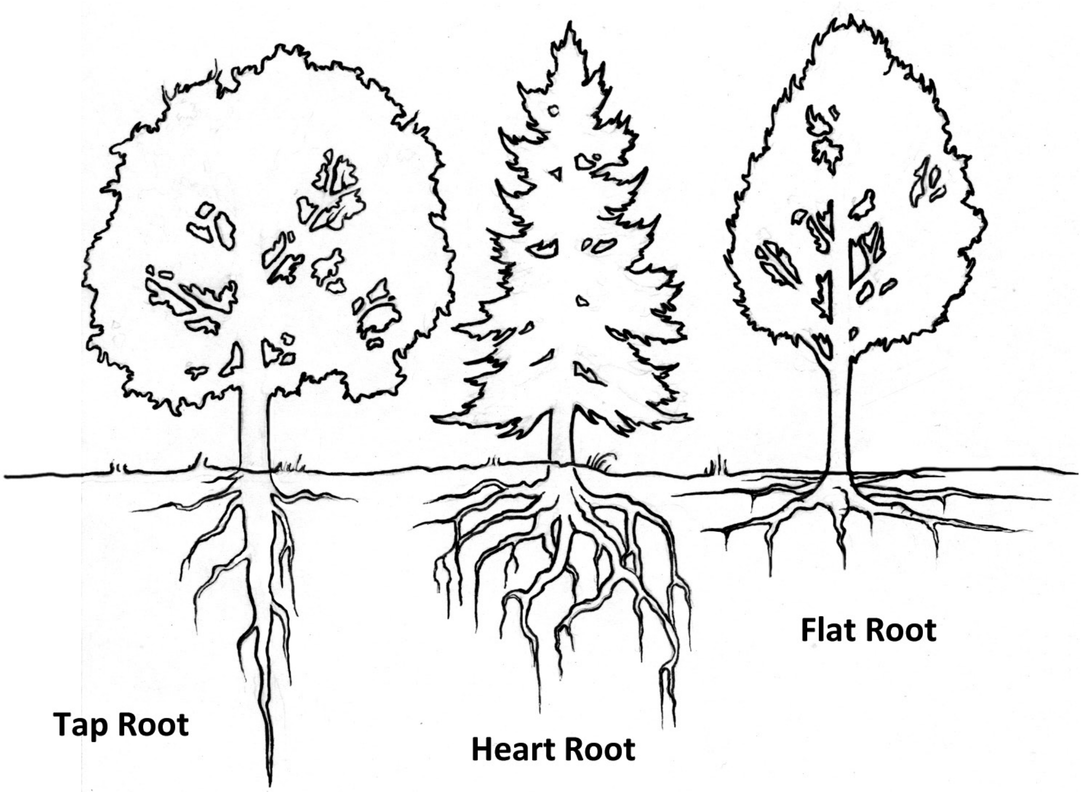


Figure 9. Major features of a root. Drawing by Robin L Quinlivan.

(**geologic erosion**) and influenced by humans (a**ccelerated erosion**). Accelerated erosion can be 10 to 1000 times more damaging than geologic erosion (Brady and Weil 2007). Examples include disturbance of soil or natural vegetation by grazing livestock, deforestation, tillage, and construction, each of which are exacerbated by high rainfall and/or steep slopes.

Globally, ~ 15 % of total land area is eroded, of which over half is severely eroded (Blanco-Canqui and Lal 2008). Soil erosion rates are greater than soil formation rates, posing a threat to sustainable agriculture (Pimentel 2006). Productive land is < 11 % of earth's total land area (Eswaran et al. 2001), yet it must supply food to the world's population (> 7 billion people). Pimentel (2006) suggested that soil is being lost at a rate that is 10 to 40 times faster than soil formation and ~ 10 million ha of cropland is lost yearly to erosion. Agriculture accounts for ~ 75 % of soil erosion worldwide (Pimentel 2006). Soil erosion is lowest in the U.S. and Europe (~ 10 metric tons ha^{-1} yr^{-1} soil lost) and much more severe in the rest of the world (~ 30 – 40 metric tons ha^{-1} yr^{-1} soil lost) where resources and incentives for implementing conservation measures are inadequate (Blanco-Canqui and Lal 2008).

Erosion is defined by the Soil Science Society of America (SSSA 2008, 19) as: "(i) The wearing away of the land surface by rain or irrigation water, wind, ice, or other natural or anthropogenic agents that abrade, detach, and remove geologic parent material or soil from one point on the earth's surface and deposit it elsewhere, including such processes as gravitational creep and so-called tillage erosion. (ii) The detachment and movement of soil or rock by water, wind, ice, or gravity."

Essentially, erosion occurs in a three-step process of detachment, transport, and deposition. The first step, detachment, is the removal of soil material from the soil mass by raindrops, running water, wind, or human/animal activities. The detached soil materials are then transported downhill by method of splashing, floating, dragging, or rolling. Sand particles are heavier than silt or clay, and therefore cannot be transported as far or at the same velocity. Silts and clays often become suspended in water and may be transported long distances. The third step, deposition, usually occurs in floodplains, fields, wetlands, lakes/reservoirs, rivers, and streams. In agricultural fields, sediment may also be deposited in front of control structures such as dry dams, terraces, or vegetative filters (e.g., riparian areas and grass waterways).

Soil erosion is divided up into different categories: rill erosion, interrill or sheet erosion, and gully erosion. **Rill** erosion is the formation of tiny channels across a soil surface that often occurs in sloping agricultural fields. **Interrill** erosion is the removal of a somewhat uniform layer of soil which is attributed to the splash effect of raindrop impact and also sheet flow. If rill erosion persists, it is likely that gully erosion will occur. **Gully** erosion is the erosion process that removes large amounts of soil and results in a narrow, deep channel.

Eventually, high amounts of erosion will destroy soil quality, which in turn, compromises long-term food and timber production. The Dust Bowl of the 1930s raised awareness to the need for soil conservation and prompted implementation of conservation practices. Several government programs geared towards soil conservation are in place to minimize and prevent unnaturally high occurrences of soil erosion by wind and water. The Food and Security Act of 1985 included conservation measures that helped reduce erosion from U.S. cropland by 1.3 billion metric tons between 1982 and 1997 (Montgomery 2007). For example, the Conservation Reserve Program (CRP) (included in the Food and Security Act of 1985) provides economic incentives to landowners who implement soil conservation measures on highly erodible cropland. In 2010, 10.7 metric tons ha^{-1} of cropland was lost in the U.S., whereas CRP land reported a total of 1.7 metric tons ha^{-1} lost to wind and water erosion (USDA 2013). Since the CRP was implemented in 1986, soil erosion has been reduced by > 7 billion metric tons (USDA 2010). Additionally, recent adoption of notill farming has contributed to a reduction in soil erosion. In a review of studies comparing conventional and notill methods, Montgomery (2007) found that notill practices reduced soil erosion by 2.5 to > 1,000 times compared to conventional methods.

Although adoption of conservation practices is increasing, there are several obstacles that land managers interested in soil conservation must overcome. At times, the initial implementation of conservation practices can be more costly than the economic return. The fear of the unknown will sometimes steer people away from adopting new conservation technologies. It is also difficult to convey the importance of soil conservation to every individual, whether it is due to lack of interest or unavailable information.

The **Universal Soil Loss Equation** (**USLE**), a model based on extensive erosion data from small plot studies across the U.S., was created by countless federal and university scientists in the mid-1900s to predict soil loss. The USLE has been used worldwide to estimate soil erosion and guide soil conservation efforts. The USLE equation accounts for slope, rainfall, soil series, topography, crop system, and management practices on a landscape. The equation has been revised over time and is now referred to as Revised Universal Soil Loss Equation, Version 2 (RUSLE2), a computer-based equation. However, to understand the principles of estimating soil erosion rates, it is important to analyze the original formula:

$$\text{USLE: } A = R * K * LS * C * P$$

where A is annual soil loss (tons ac^{-1} yr^{-1}), R is erosivity factor, K is erodability factor, LS is slope length and slope steepness factor, C is cover and management factors, and P is conservation practices factor.

The e**rosivity factor** (**R**) assesses the total rainfall, intensity, and seasonal distribution of rainfall in a geographic location. The R factor accounts for the driving force of rill and interrill erosion. In other words, the R factor recognizes that high intensity rainfall will cause more catastrophic damage than a lower intensity rainfall event. The e**rodability factor** (**K**) assesses how susceptible the soil is to erosion, which includes a soil's infiltration capacity, texture, and its structural stability/integrity.

Only three of the factors in the equation can be manipulated. The **slope length** factor (**LS**) can be changed by reshaping the land into terraces, dry dams, or other erosion control structures. The **cover factor** (**C**) is probably the easiest factor to change. In forests, limiting harvesting and road structures can greatly improve this value. In agriculture fields, perennial crops (e.g., alfalfa, orchard grass) that retain groundcover in the winter versus annually harvested crops (e.g., soybeans, corn) will improve the C factor, as will planting cover crops during times the field would normally be fallow. The **conservation practices factor** (**P**) can be changed by installing various conservation structures and implementing contour cropping wherever necessary. An example of a conservation structure would be installing a water bar after a timber harvest. Water bars are used to divert water away from logging roads and into vegetated areas, decreasing erosion of these roads.

Soil Quality

The basic definition of **soil quality** is the capacity of a soil to function (Karlen et al. 1997). This functional definition balances the physical, biological, and chemical components of soil. The expanded version of this functional definition is "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation" (Karlen et al. 1997). What constitutes good soil quality may be different according to land use and/or geographic region. For this reason, Karlen et al. (1997) suggests a relational approach to evaluating soil quality, as opposed to an absolute approach. Similarly, Doran et al. (1996) suggest that soil quality should be evaluated based on how well a soil functions within its specific ecosystem (agriculture, urban, etc.). For example, in an agricultural field, the capacity of a soil to function at sustaining crop growth would depend on several soil characteristics including bulk density, soil moisture, infiltration, and biological activity, to name a few. Many of these properties can be changed by management (e.g., infiltration and organic matter content) and soil quality can be improved according to its function. As seen throughout this article, soil also affects water quality, air quality, and biotic quality. Protecting and/or improving soil quality can provide a stepping stone to improving environmental quality as a whole. For example, planting cover crops when a field would otherwise be bare, helps reduce soil erosion and aids in soil and nutrient retention on site, limiting its transportation to waterways where water quality would be affected.

Land Use and Soils

Cultivated and Grazed Soils

In cultivated areas, soils are mechanically worked to break up compaction and amended with fertilizers, herbicides, and pesticides to enhance crop production and provide weed and pest control. These processes can expose bare mineral soil and increase the risk of water and wind erosion. Under improper management, agriculture can devastate the landscape. For example, intense cotton farming in the southeastern United States was blamed for the loss of 10 to 30 cm of topsoil (with an average of ~ 18 cm), which led to the accumulation of large volumes of legacy sediment in the floodplains (Trimble 1974). Similarly, poor farming practices coupled with a drought, caused millions of acres of farmland to become lost during the time known as the "dust bowl" or "dirty thirties" era. Fortunately, recent farming practices have adopted environmentally conscientious methods to reduce soil erosion and other impacts on the environment. Farmers now understand that crop selection and farm management decisions should be based on soil characteristics and land conditions. Farmers seek to maximize yields while simultaneously creating a sustainable farming system.

Land use change can have significant impacts on soil quality. If cultivated areas are abandoned, shrubs and trees quickly reoccupy the site; however, carbon pools and nutrient dynamics within the soil may be slow to recover. For example, following a 30-yr succession in North Carolina, most available carbon was allocated to aboveground standing biomass and not towards soil organic matter accumulation (Richter et al. 1995).

Impacts of grazing on soils fall into two categories: 1) physical impacts from animals and 2) chemical and biological impacts from animal waste. Livestock, such as cattle, compact the soil structure and typically consume vegetation in heavily used areas, such as feeding or watering sites. As a result, the compacted bare areas are more susceptible to erosion and surface runoff. Waste associated with livestock is also a problem. Urine and feces from livestock can create hotspots for nutrients and bacteria. In these areas the vegetative uptake often is much lower than the supply of nutrients. Nitrogen, for instance, either leaves the site through groundwater or surface runoff or is denitrified under optimal conditions. Oftentimes in heavily grazed land, the carbon supply for completed denitrification is lacking, thus incomplete conversion of NO_3 to N_2 gas occurs, resulting in nitrous oxide pollution into the atmosphere.

Forest Soils

Forest soils tend to be on land unsuitable for row-crop agriculture or grazing. Thus, forests are typically in areas of steep topography, poor drainage, or where soils are too rocky for farming. Contrary to agricultural soils, forest soils typically have an intact litter layer that can protect soils from temperature and moisture fluctuations and from wind and water erosion.

Forest Harvesting. Forest harvesting is a common occurrence in the United States and around the world. Harvesting provides the nation with wood products needed in our daily lives. Along with these benefits come potential damages to our environment. The majority of compaction in a forest is caused by forest harvesting procedures. Surprisingly, the primary source of erosion during a harvest results from the construction of roads into the forest and not from the actual logging practices, as one might expect. It is the job of foresters and ecologists to conduct sustainable forest harvesting using best management practices in an effort to reduce site impacts. Harvesting timber has a variety of different effects on the soil, depending on the kind of harvest and caution used while harvesting. The harvesting process opens up the canopy, which in turn allows for more light to hit the forest floor. This increase in light exposure changes the chemical processes occurring in the soil. These changes can then shift the plant and animal species composition found on the site. The exposure of mineral soil from harvesting can increase the potential for erosion and leaching of nutrients.

Loggers use a variety of methods for harvesting timber. Common equipment includes log skidders, feller-bunchers, and cable logging, each with their own pros and cons. Heavy machinery equipped with wide tracks instead of pressured wheels reduces the degree to which the machine compacts the soil. Types of machinery used often depend upon the region. In places like the Midwest where there are large tracts of agricultural land and few tracts of forestland, access to state-of-the-art logging equipment is limited. Detailed guidelines on Best Management Practices (BMPs) associated with forest harvesting are described in "Guiding Principles for Management of Forested, Agricultural, and Urban Watersheds" (Edwards et al. 2015, this issue).

Long-term site productivity continues to be a concern to natural resource managers. An increase in the industries of biofuel production, whole-tree harvesting, woodchip utilization, and wood pellets have researchers and managers studying how long forests can sustain the continuous removal of biomass from forests. A potential short-term solution to this problem could be the introduction of fertilization into forest ecosystems to replenish nutrients exported from the site via whole-tree removal. Large-scale fertilization of forests has increased in the last decade. However, it is unclear how large-scale fertilization affects long-term site productivity because a longer monitoring period is needed to assess the changes in site quality.

Fire. Fire plays a key role in shaping the structure of a forest community; however, fire can also be both beneficial and detrimental to forest soils. Fire can alter the chemical and physical status of soils, impact hydrology, increase soil erosion, and influence the biotic structure of soils. The severity of fire impacts generally depends on burn intensity, climatic conditions following the burn, landscape, and soil characteristics. Following intense burns, nutrient cycling can be disrupted and lead to leaching, volatilization, and/or transformation. When vegetation is consumed by fire, some of the litter-incorporated N, P, K, Ca, Mg, Cu, Fe, Mn, and Zn are volatilized and lost from the system, while metallic nutrients such as K, Ca, and Mg are converted into oxides and accrued in ash (DeBano et al. 1998). The long-term effects of fire on the soil nutrient status can be significant (Williard et al. 2005). Repeated low intensity fires, such as prescribed fires or single large fires, can reduce soil nitrogen pools significantly (Gagnon 1965; Carreira et al 1994). In fact, Gagnon (1965) documented that a historical fire (20 years earlier) exhibited long-term effects on soil nitrogen and tree nutrition. Vegetation following a 500 km^2 burn showed deficiencies of both nitrogen and phosphorus in foliar analyses.

Using properly executed prescribed fire may actually increase nutrient uptake and provide greater surface roughness through the establishment of dense vegetation post-burn. The increased surface roughness from the newly established and vigorous vegetation growth can reduce surface runoff velocities, in turn reducing the risk of soil erosion. Additionally, the flush of vegetation can increase nutrient uptake, thereby retaining the nutrients on site. Conversely, uncontrolled fire can be detrimental to a forest ecosystem. Under conditions where all vegetation is consumed, the risk of soil erosion is increased, nutrient uptake by plants may be reduced, and high stream temperatures may result. As vegetation is removed, evapotranspiration in the watershed is reduced, thus providing a greater volume of water that can produce surface runoff. Increased overland flow combined with a consumed litter layer can lead to serious erosion problems and result in higher stream discharges. To compound the problem, intense burns can produce hydrophobic conditions in the soil that ultimately reduce infiltration and increase surface runoff. Hydrophobic conditions are generally produced during moderate to high severity burns (175° - 200° C), in coarse textured soils, and at lower soil water contents (DeBano et al. 1998). Both nutrient runoff and erosion can be exacerbated in areas of steep slopes and high rainfall.

Soil heating is the primary mechanism by which fires impact a soil's physical and biotic structure (Neary et al. 1999). The degree of soil heating during a fire is highly variable across a site, but depends on fuel characteristics (size, arrangement, and moisture status), soil properties (texture, structure, and both the moisture and organic content), and fire behavior (intensity and duration). Generally 8 - 10 % of the aboveground heat can be transferred to the soil, resulting in higher soil temperatures (DeBano et al. 1977). Fuels differ in terms of maximum temperatures produced and the duration that they can burn. For example, downed logs and stumps can burn for days following the passage of the fire front, which will induce a more sustained soil heating. Further, finer textured soils (i.e., increased clay content) tend to transfer heat better than quartz-based soils.

Organic content of soils can also be impacted by fire. The consumption of soil organic matter, which is a cementing agent in soils, can result in a loss of soil structure. Reduced structure can reduce porosity, increase bulk density, and decrease infiltration and percolation. Structure takes time to rebuild, and under severe conditions where the soil biota was impacted, the recovery can be even greater since soil invertebrates play a key role in maintaining soil porosity. The degree to which soil invertebrates are impacted relates to soil temperature and moisture. Biota can tolerate higher temperatures in dry soils compared to moist soils.

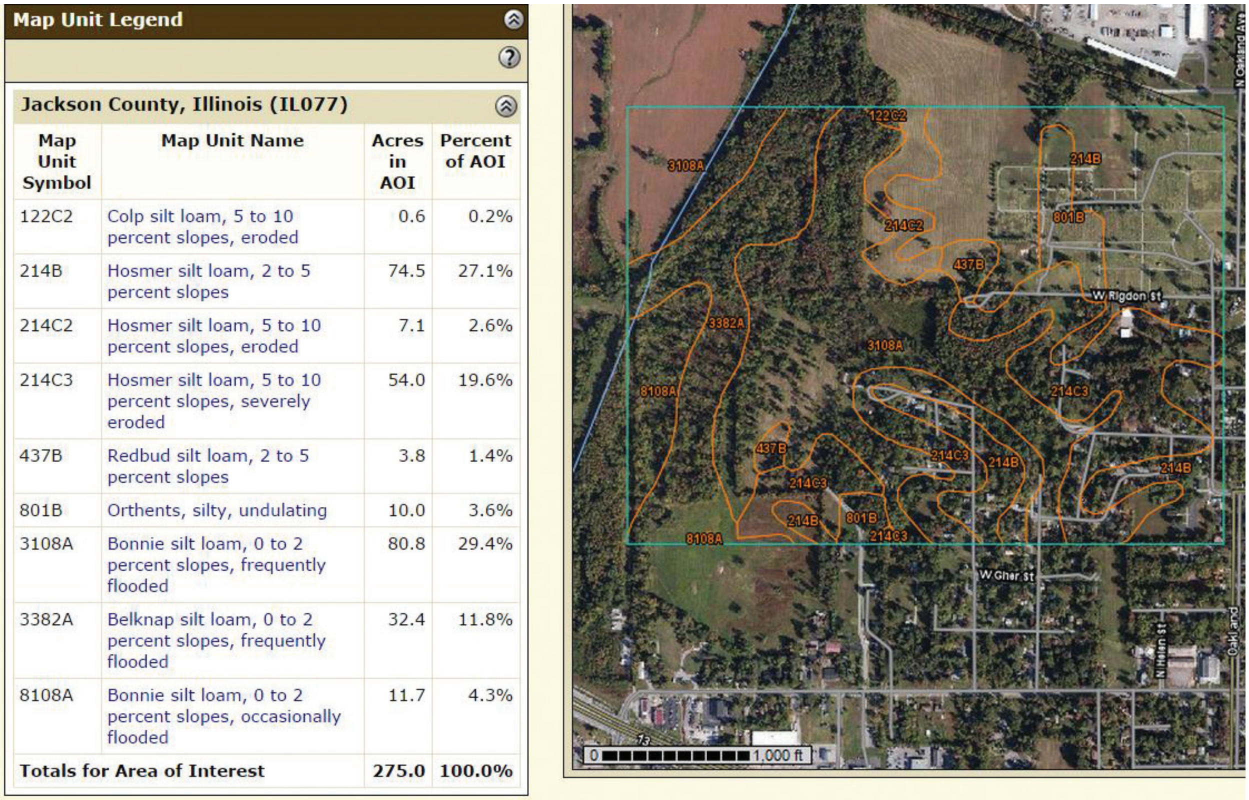
Urban Soils

Soils are modified by anthropogenic activities in urban environments. The impacts of urban infrastructure on the environment create changes in the physical, chemical, and biological properties of urban soils. Notably, pore space is reduced due to soil compaction from building and road engineering, thereby increasing soil bulk densities. Additionally, the loss of pore space and soil structure combined with increased impervious surfaces leads to reduced infiltration and increased surface runoff. Compaction may also lead to poor establishment of plant communities in urban areas. Pouyat et al. (2007) found that K, P, bulk density, and pH were higher in urban residential soils compared to forest soils, likely a result of lawn fertilizers and intensity of use. However, other soil variables measured were related to parent material rather than land use, including soil texture, Al, Fe, and other micronutrients (Pouyat et al. 2007). While urbanization can impact some soil characteristics, especially bulk density and infiltration, other surface soil characteristics are still predetermined by parent material. Urban soils can recover over time. Scharenbroch et al. (2005) found that as time since the initial disturbance of urban soils increased and allowed for soil development, bulk densities decreased and organic matter and biological activity increased. Time is a soil-forming factor that plays an important role in reducing the impacts of urbanization on soil characteristics.

Knowledge of urban soil properties can lead to better management of water resources in terms of both quantity and quality. Duration of irrigation in urban areas should be based on the water holding capacity of the soil. Organic matter can be incorporated into the soil to increase pore space and soil aggregate stability, thereby increasing infiltration and nutrient retention and reducing runoff. Soil texture should be considered when determining fertilizer management. For instance, sandy soils exhibit poor nutrient retention and nutrients that leach below the rooting zone may eventually travel to ground and surface waterbodies, impacting water quality. Nitrate is especially mobile and nitrate that is not used by plants or microbes is easily transported from the soil water to groundwater.

Evaluating Your Soil

This article has provided an introduction to soils and stressed the importance of considering soil characteristics when making land management decisions. How does one learn about the soil specific to a given watershed in order to make sound management decisions? There are many helpful internet sites available to land and watershed managers; one place to start is a soil survey. The USDA NRCS operates the Web Soil Survey (Soil Survey Staff). Users obtain soils information by entering coordinates, interactively selecting a field area with a map interface, or by importing a shapefile. An example of soil series data produced from a user-defined area of interest in Jackson County, IL, is provided in Figure 10. Soil surveys contain information on the suitability and limitations of soils in the specified geographic area and are created from on-site surveys of the soil profile collected by soil scientists. These surveys can help determine if a site is suitable for a basement, prone to flooding, or a good site for a septic system, among many other applications. It should be noted that spatial variability is inherent in soils and a 100 hectare site may contain several different soil series with contrasting soil properties. If interested in the nutrient, organic



Map Unit Legend

Jackson County, Illinois (IL077)

Map Unit Symbol	Map Unit Name	Acres in AOI	Percent of AOI
122C2	Colp silt loam, 5 to 10 percent slopes, eroded	0.6	0.2%
214B	Hosmer silt loam, 2 to 5 percent slopes	74.5	27.1%
214C2	Hosmer silt loam, 5 to 10 percent slopes, eroded	7.1	2.6%
214C3	Hosmer silt loam, 5 to 10 percent slopes, severely eroded	54.0	19.6%
437B	Redbud silt loam, 2 to 5 percent slopes	3.8	1.4%
801B	Orthents, silty, undulating	10.0	3.6%
3108A	Bonnie silt loam, 0 to 2 percent slopes, frequently flooded	80.8	29.4%
3382A	Belknap silt loam, 0 to 2 percent slopes, frequently flooded	32.4	11.8%
8108A	Bonnie silt loam, 0 to 2 percent slopes, occasionally flooded	11.7	4.3%
Totals for Area of Interest		**275.0**	**100.0%**

Figure 10. Soil survey data of an area in Jackson County, IL. Produced from Web Soil Survey (Soil Survey Staff).

matter content, or pH of your soil for gardening or farming, soil samples can be taken or shipped to various laboratories around the country that will provide basic to extensive soil information. These soil data can be useful to develop appropriate land management practices.

Conclusion

Watershed management, from urban to rural environments, must incorporate the functionality of the soils within the watershed. Understanding watershed soil characteristics allows for a greater understanding of the processes controlling erosion, water movement and storage, pollutant runoff, and site productivity, among others. Soil is a finite resource and as such it is important for watershed managers to consider both soil quality and conservation in watershed management plans. In terms of conservation, it is important to minimize erosion through structural and/or vegetative measures. Measures should not only be cost-effective, but also sustainable and practical based on the land conditions. In terms of soil quality, management decisions must consider the capacity of the soil to function within the framework of the ecosystem.

Soil Information Resources

Web Soil Survey:
http://websoilsurvey.nrcs.usda.gov/

"Feel" Method Guide to Soil Texture:
http://www.nrcs.usda.gov/Internet/FSE_MEDIA/nrcs142p2_050352.jpg

Soil Taxonomy:
http://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/survey/class/taxonomy/

Official Soil Series Descriptions:
http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid=nrcs142p2_053587

Acknowledgment

This work was supported by funds from the USDA McIntire Stennis Cooperative Forestry Research Program.

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