ILLINOIS

SOILS

Soils Study Guide

ILLINOIS ENVIROTHON

Acknowledgements

The guide was reviewed with support from Natural Resources Canada and Agriculture Canada.

Illinois Envirothon reviewed material and reconfigured for Illinois purpose

Updated: December 2016

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Learning Objectives

Overall Objectives

Students must be able to…

A. Understand and describe the physical properties of soil and the processes of soil formation
B. Understand and describe the chemical properties of soil and the chemical processes of soil formation
C. Understand and describe the biotic and abiotic characteristics and processes of soil ecosystems
D. Understand and describe practices involved in the conservation and management of healthy soil ecosystems and sustainable land use

Specific Objectives

Students must be able to…

A. Understand and describe the physical properties of soil and the processes of soil formation

1. Understand and describe soil structure in terms of three components: form, stability, and strength
2. Understand and describe how different amounts of organic matter affect and are affected by soil structure and texture
3. Identify and explain factors that influence soil temperature
4. Understand and describe the factors affecting soil formation: additions, losses, translocations and transformations

B. Understand and describe the chemical properties of soil and the chemical processes of soil formation

1. Understand and describe how soil pH affects plant growth
2. Understand and describe the cation exchange process and relate it to soil fertility
3. Identify and explain the benefits of soil organic matter to soil chemistry
4. Identify and explain the essential nutrient elements in soil and describe how they affect soil fertility

C. Understand and describe the biotic and abiotic characteristics and processes of soil ecosystems

1. Identify types of soil organisms and their functions within a soil ecosystem
2. Understand and describe the carbon cycle and the nitrogen cycle and their effects on soil chemistry and subsequent plant growth
3. Describe the effects of each type of erosion on the landscape and capability for various kinds of plant growth
4. Explain how soil composition and fertility can be altered in an ecosystem and identify the possible consequences of such changes
5. Know that plants must receive essential micronutrients and macronutrients from the soil in order to be healthy, and understand that soil fertility relates to the physical and chemical properties of the soil in addition to the quantity of nutrients

D. Understand and describe practices involved in the conservation and management of healthy soil ecosystems and sustainable land use

1. Identify and describe best management practices for a variety of land uses, including agriculture and forestry, and explain why these management practices are used
2. Describe how invasive species can affect soil ecology
3. Understand and describe the effects that climate change has on soil ecology
4. Identify and describe erosion control methods (windbreaks, crop rotation, drainage, etc.)

Application/Analysis

Students must be able to:

1. Collect and interpret data using the following field equipment and hands on evaluation:
   - Soil triangle to determine soil class
   - Munsell soil color chart or other color charts
   - Slope
   - Nutrients

2. Describe and classify a soil profile
3. Identify and measure soil horizons in a soil pit, photograph or sample
4. Name and map the soil orders of the US and identify them on a map
5. Identify soil types according to textural characteristics
6. Classify soil structure according to aggregate characteristics (i.e. granular, blocky, columnar, platy, massive)
7. Relate stream velocity to sediment sorting

Evaluation/Synthesis

Students must be able to:

1. Relate how soil, water and air are interrelated
2. Use data and other observations of soils to explain prevalent vegetation in an area
3. Predict the types of soil organisms that would be found within a given soil type
4. Assess a site for evidence of erosion
5. Make recommendations on how to implement erosion control
6. Make on-site recommendations on how to improve soil quality

Tools and Apps

The following tools are recommended resources that can help you better prepare for the Envirothon program.

Envirothon Resources

Illinois Soil Classification

Applications and Interactive Websites

SoilWeb: USDA-NRCS soil survey data. The application retrieves graphical summaries of soil classification and soil properties associated with any location in the United States. http://websoilsurvey.sc.egov.usda.gov

ArcGIS: great lesson plans and resources to introduce soils into your classroom http://resources.arcgis.com/en/communities/soils/

2.0 What is Soil?

2.1 The Significance of Soil

As you look around you, you may recognize that every object is directly or indirectly obtained from the soil. The clothes you are wearing may be derived from plants that once grew on soils. The road you travel on to get to school is constructed on the solid body of soil. The water you drink may be derived from clean groundwater that was filtered with the help of soils. All the agricultural, forestry, and wilderness areas in Illinois would disappear entirely without the small accumulation of topsoil that exists on this vast land. Clearly, soils provide for many of our basic needs.

2.1.1 Ecosystems

Different bodies of soils vary in nature in their physical, chemical, and biological properties. Some soils are rich in **nutrients** and **organic matter**; others are thoroughly leached. Some have a high **water-holding capacity**; some allow rapid water **infiltration**. Soils also differ in age, depth, compaction, and temperature. The varying types and conditions of soils in a region are crucial in determining the species of plants and animals that can be supported in an ecosystem. Without diverse soils, the biodiversity that exists on earth would rapidly disappear.

Within the terrestrial ecosystem, all living organisms depend on soil. Trees and plants obtain water and nutrients from the soil and convert them into energy that can be used by a variety of different consumers and soils serves as the structural **medium** supporting the roots of plants. Some living organisms such as bacteria, fungi, mites, earthworms, snails, and insects exist within the body of the soil. Other organisms such as turtles lay their eggs inside the soil. The interrelated web of plant and animal communities cannot exist without the soil.

2.1.2 Agriculture

Soils are often referred to as the medium of growth. Without soil, there would be no means of providing crops with the water and nutrients that are essential for growth Illinois' 74,300 farms cover nearly 27 million acres -- about 75 percent of the state's total land area. Illinois is a leading producer of soybeans, corn and swine. The state's climate and varied soil types enable farmers to grow and raise many other agricultural commodities, including cattle, wheat, oats, sorghum, hay, sheep, poultry, fruits and vegetables. Illinois also produces several specialty crops, such as buckwheat, horseradish, ostriches, fish and Christmas trees. (https://www.agr.state.il.us/facts-about-illinois-agriculture/)

Soils also provide the medium for growth of plant and animal materials for natural fabrics and cloths, including cotton, wool, silk, and leather. In many cases, soils also provide the natural dyes used to color these fabrics. The use of soil for modern agriculture, just like in ancient civilizations, causes numerous complications that may degrade the quality of soil and render agriculture impossible. The inappropriate use of heavy equipment for the purpose of tillage often causes soil compaction, preventing precipitation from penetrating the soil, and resulting in runoff and erosion. Irrigation often leaves salts at the root zone of crops, preventing uptake of water. Addition of pesticides, insecticides, and fungicides destroys certain soil organisms and inhibits the natural function of the system.

2.1.3 Water Supplies

Soil also has the ability to acts as a natural purifying and filtering agent for the world's **groundwater** supplies. All rain and wastewater that percolates down to the groundwater is chemically and biologically treated to become drinkable once again. The sand and silt components of the soil sieve out any solid components, while charged surfaces of clays absorb any hazardous contaminants that have been dissolved in the water. Meanwhile, billions of soil organisms act to eliminate pathogens, viruses, dissolved solids, and other color and taste problems. Soil protozoa prey on pathogens as food. Bacteria and fungi produce antibiotics that destroy harmful pathogens. In addition, the new environment of the soil (temperature, pH, and nutrients) creates conditions that are intolerable for pathogens.

2.1.4 Engineering

Not only do soils provide an engineering medium for the foundation of roads, houses, and train tracks, they also provide the materials – wood, brick, sand, and gravel – used to build these facilities. The properties of soils place restrictions on the location suitable for building structures and influence their long-term stability. These nine site and soil properties are critical to evaluate for building selection: (A) **surface texture**, the amount of sand silt and clay in the soil; (B) **permeability**, the rate at which water enters and passes through the soil; (C) **depth of soil to bedrock**, including both topsoil and subsoil; (D) **slope**, steepness and length of the slope; (E) **erosion hazard**, the amount of topsoil currently on the site and the potential for future losses; (F) **surface runoff**, the rate at which water flows off the site based on slope, drainage and texture; (G), **shrink-swell of the soil**, which involves changes in volume based on soil wetness; (H) **water table**, the depth at which water occurs in the soil both seasonally or permanently; and (I) **flood hazards**, the frequency that water from storm runoff inundates the site.

http://anr.ext.wvu.edu/soil/homesite-soilsite-review

2.1.5 Recycling

Organic matter is cycled and recycled time and again as nutrients from mineral soil are converted to organic plant matter, consumed by animals to become flesh, and returned again to soil to repeat the same cycle. Decomposers that live in the soil, including fungi, earthworms, snails, slugs, arthropods, lichens, and moss, break down dead organic matter to their mineral form to be taken up as nutrient by autotrophs.

3.0 Quaternary Glaciations in Illinois

3.1 Origin of the Glaciers

Over the past 1.6 million years, known as the Quaternary (kwa-TURN-ah-ree) Period of geologic time, most of the northern hemisphere above the 50th parallel was repeatedly covered by glacial ice. The cooling of the earth's surface began at least 2 million years ago, and with that cooling, ice sheets eventually formed in sub-arctic regions and spread outward until they covered the northern parts of North America. With ongoing climatic change during this period, these ice sheets would form and reform many times.

Early studies of the glaciated landscape concluded that four separate glacial episodes had occurred in North America. The deposits from each episode were separated from each other by buried soils, which formed on the land during warmer intervals between glaciations. More recent studies have shown that there were more than four glaciations, but the actual number is not yet known. These studies, based on buried soils and glacial deposits, estimate 4 to 8 episodes of ice advance and melting over Illinois. We now know that the older glacial sediments are more complex than originally thought and probably represent more than one episode. Until we know more, all of the glacial deposits before the Illinois Episode (from 300,000 to 125,000 years ago) are classified as pre-Illinoian deposits.

The North American ice sheets developed when the mean annual temperature was perhaps 4° to 7°C (7° to 13°F) cooler than it is now and winter snows did not completely melt during the summers. Because this time of cooler conditions lasted tens of thousands of years, thick masses of snow and ice accumulated to form glaciers. As the ice thickened, the great weight of the ice and snow caused the glaciers to flow outward at their margins, in several instances for hundreds of miles. As the ice sheets expanded, the areas in which snow accumulated probably also increased in extent.

Several times, huge tongues of ice, called lobes, flowed southward from two different centers, one east and one west of present-day Hudson Bay, and converged in the central lowland between the Appalachian and Rocky Mountains. There the glaciers made their farthest advances to the south. The sketch at right shows the centers of flow, the general directions of flow from the centers, and the southern extent of glaciation. Because Illinois lies entirely in the central lowland, it was invaded by lobes from both accumulation centers.

3.1.1 Effects of Glaciation

Quaternary glaciers and the waters melting from them changed the landscapes they covered. The glaciers scraped and smeared the landforms they overrode, leveling and filling many of the minor valleys and even some of the larger ones. Moving ice carried colossal amounts of rock and earth, commonly for hundreds of miles; the glaciers scoured the land surface and kneaded much of the rock debris into the moving ice. The continual floods of glacial meltwaters entrenched new drainage ways and deepened old ones, and partly refilled them with the great quantities of rock and earth carried by the glaciers. According to some estimates, the amount of water that was drawn from the sea and changed into ice during a glacial episode lowered the sea level by 300 to 400 feet below its present level. When these continental ice sheets melted, tremendous volumes of water eroded and transported sediments.

In most of Illinois, glacial and meltwater deposits buried the previous rocky, low, hill-and-valley terrain and created the flatter landforms that became our prairies. The glaciers deposited across roughly 90% of the state a mantle of ground-up rock debris, gravel, sand, and clay that at points reaches thicknesses of 400 to 500 feet. These deposits are of incalculable value to Illinois residents because they are the parent material of our rich soils, the source of drinking water for much of the state, and provide large amounts of sand and gravel for construction.

3.1.2 Glacial Deposits

Drift is the term for all the deposits of earth and rock materials moved by glacial activity. Till is the type of drift deposited directly by glacial ice. Because till was not moved much by water, this sediment is unsorted, containing particles of many different sizes and compositions. It is also unstratified (unlayered). A till may contain materials ranging in size from microscopic clay particles to large boulders. Most tills in Illinois are pebbly clays with only a few boulders. For descriptive purposes, a mixture of clay, silt, sand, and boulders is called diamicton. This term describes a deposit that could be interpreted as till or as a product of a different process called mass wasting, which includes such things as rockslides or other similar gravity-propelled earth movements.

End moraines are the arc-shaped ridges that formed when till piled up along a glacier’s leading edge when the ice was melting at roughly the same rate as the flowing ice moved forward. Till also formed ground moraines, or till plains, which have gently undulating surfaces formed as the ice front melted back. Deposits of till identify areas once covered by glaciers. The many alternating ridges and plains in northeastern Illinois are the successive end moraines and till plains formed by the retreating Wisconsin Episode glaciers (about 25,000 to 13,500 years ago).

Outwash is the sorted and stratified sediments deposited by meltwater flowing away from the glacier. Outwash deposits are layered in beds because the flow of water that moved the material varied in gradient, volume, velocity, and direction. As a meltwater stream carried the rock materials along, it sorted them by size. As stream velocity decreased, heavier gravels and cobbles were deposited before fine sands, silts, and clays, which were deposited farther downstream. Typical Quaternary outwash in Illinois consists of multilayered beds of sands and gravels and some silts. These beds look much like modern stream deposits in some places. Outwash tends to be coarser and less weathered than stream sediment (alluvium), which is generally finer than medium sand and contains variable amounts of weathered rock debris.

Meltwater deposits are found not only in the area once covered by the glaciers but also in areas far beyond it. Meltwater streams ran off the top of the glacier, in crevices within the ice, and under the ice. In some places, the cobble-gravel-sand filling of the bed of a stream that flowed within or under the ice is preserved as a sinuous ridge called an esker. Some eskers in Illinois are made up of sandy, silty, gravelly deposits and contain mass-wasted diamicton material. Cone-shaped mounds of coarse outwash, called kames, were formed where meltwater plunged through crevasses in the ice.

The finest outwash sediments, the silts and clays, formed bedded deposits in the ponds and lakes that filled glacier-dammed stream valleys, the low-lying areas on till plains, and some low till plains where meltwaters were diked behind end moraines. Meltwater streams that entered a lake rapidly lost velocity and dropped the sands and gravels they carried, forming deltas at the edge of the lake. Very fine sands and silts were commonly redistributed on the lake bottom by wind-generated currents, and the clays, which stayed in suspension longest, slowly settled out and accumulated with them. Along the ice front, meltwater ran off in innumerable shifting, cross-cutting, and short-lived streams (called braided streams), which laid down an outwash plain, a broad, flat blanket of outwash. Outwash was also carried away from the glaciers in valleys cut by floods of meltwater. The Mississippi, Illinois, and Ohio Rivers occupy valleys that were major channels for meltwaters and that were greatly widened and deepened during the greatest meltwater floods. When the floods waned, these valleys were partly filled with outwash far beyond the ice margins. Such outwash deposits, largely sand and gravel, are known as **valley trains**. Valley train deposits may be both extensive and thick. For instance, the long valley train of the Mississippi River Valley is up to 200 feet thick in places.

3.2 Loess, Eolian Sand, and Soils

One of the most widespread types of sediment resulting from glaciation was carried not by ice or water, but by wind. **Loess** (rhymes with “bus”) is the name given to windblown deposits dominated by silt-sized particles. Most of the silt was derived from wind erosion of the valley trains. Wind action also sorted out sand, which commonly formed sand dunes on the valley trains or on the adjacent uplands. In places, sand dunes have migrated up to 10 miles away from the principal source of sand. Flat areas between dunes are generally underlain by eolian (windblown) sand that was usually reworked by water action. On uplands along the major valley trains, loess and eolian sand are commonly interbedded. With increasing distance from the valleys, the eolian sand thins and disappears, often within one mile from the valleys.

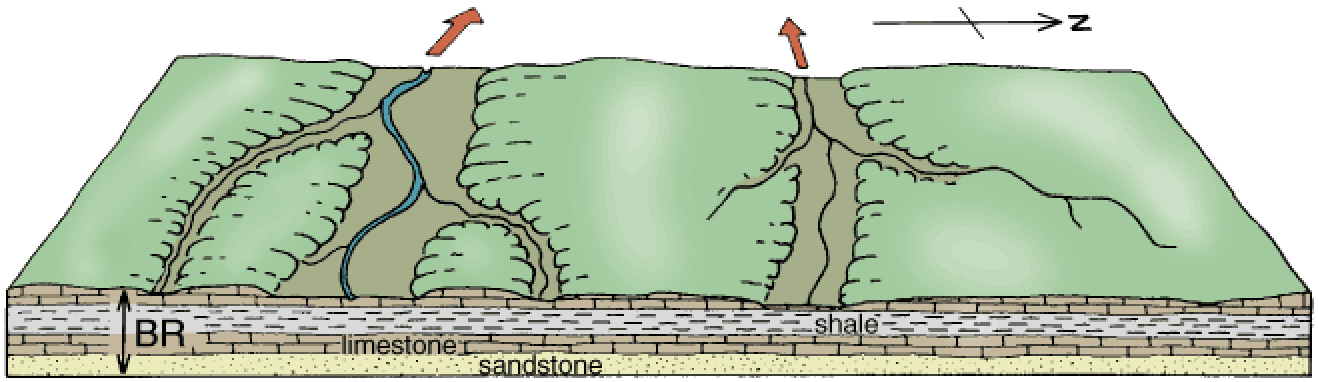
Eolian deposition occurred when certain climatic conditions, most likely following a seasonal pattern, were met. Deposition was probably in the fall, winter, or spring when low precipitation volumes and low temperatures caused meltwater floods to abate, exposing the surfaces of the valley trains and permitting them to dry out. Throughout the Quaternary Period, prevailing westerly winds deposited loess more thickly on the east sides of the source valleys. Although the loess thins rapidly away from the valleys, it extends over almost all of Illinois.

Each glacial episode was followed by an interglacial episode that began when the climate warmed enough to melt the glaciers and their snowfields. During these warmer intervals, when the climate was similar to that of today, drift and loess surfaces were exposed to weather and the activities of living things. Consequently, over most of the glaciated terrain, soils developed on the glacial deposits and altered the composition, color, and texture of the deposits. Such soils were generally destroyed by later glacial advances, but some were buried. Those that survive serve as “key beds,” or stratigraphic markers, and are evidence of the passage of a long interval of time.

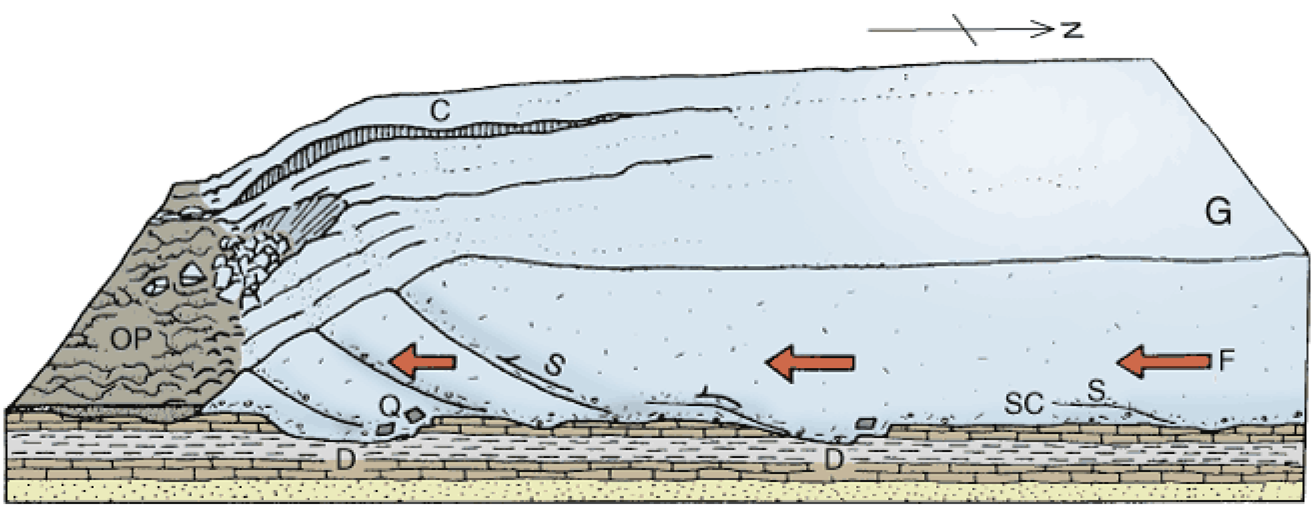
3.3 Glaciation in a Small Illinois Region

These diagrams show how a continental ice sheet might have looked at various stages as it moved across a small region in Illinois. The diagrams illustrate how the ice sheet could change the old terrain and create a landscape like the one we live on. To visualize how these glaciers looked, geologists study the landforms and materials left in the glaciated regions, as well as present-day mountain glaciers and polar ice caps.

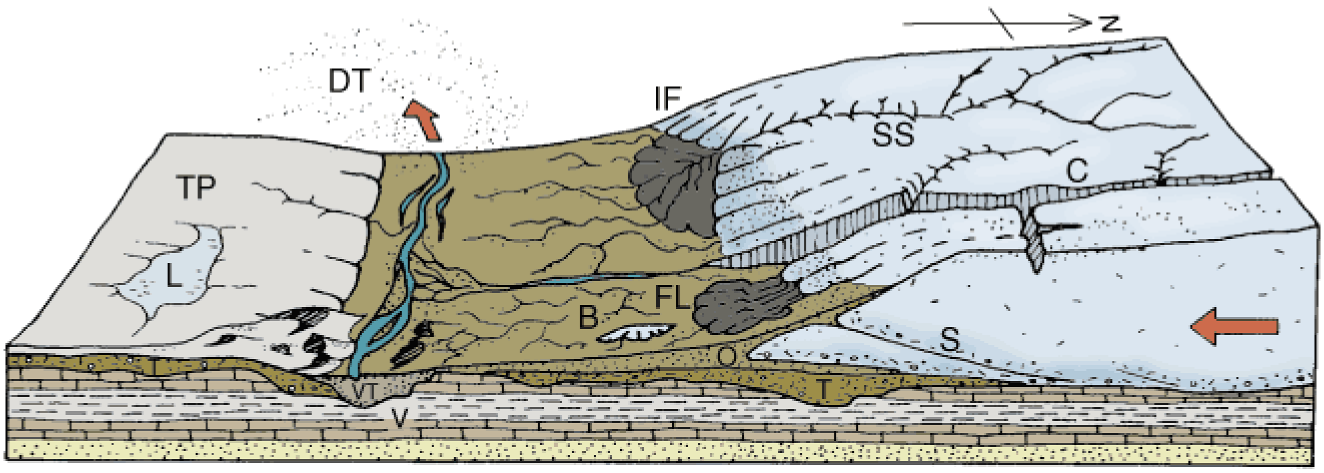
The block of land in the diagrams is several miles wide and about 20 miles long. The vertical scale is exaggerated; layers of material and landforms are drawn proportionally thicker and higher than they actually are so that they can be easily seen.



***1 The Region Before Glaciation** — Like most of Illinois, the region illustrated is underlain by almost flat-lying beds of sedimentary rocks—layers of **sandstone**, **limestone**, and **shale**. Millions of years of erosion have planed down the **bedrock** (BR), creating a terrain of low uplands and shallow valleys. A residual soil weathered from local rock debris covers the area but is too thin to be shown in the drawing. The streams illustrated here flow westward and the one on the right flows into the other at a point beyond the diagram.*



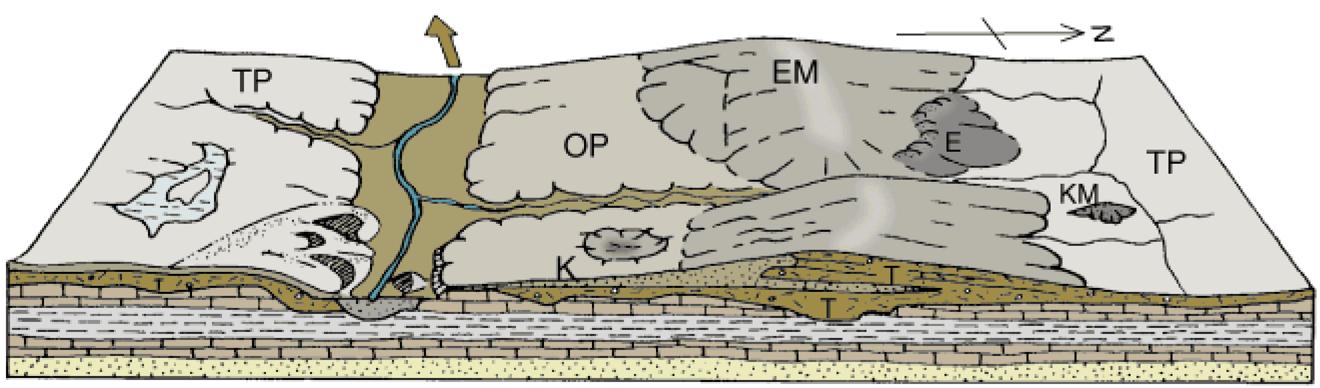
***2 The Glacier Advances Southward** — As the glacier (G) spreads out from its ice snowfield accumulation center, it scours (SC) the soil and rock surface and quarries (Q)—pushes and plucks up—chunks of bedrock. The materials are mixed into the ice and make up the glacier's "load." Where roughness in the terrain slows or stops flow (F), the ice "current" slides up over the blocked ice on innumerable shear planes (S). Shearing thoroughly mixes the load. As the glacier spreads, long cracks called "crevasses" (C) open parallel to the direction of ice flow. The glacier melts as it flows forward, and its melt-water erodes the terrain in front of the ice, deepening (D) some old valleys before ice* *covers them. Meltwater washes away some of the load freed by melting and deposits it on the outwash plane (OP). The advancing glacier overrides its outwash and in places scours much of it up again. The glacier may be 5,000 or so feet thick in Canada and tapers to the margin, which was probably in the range of several hundred feet above the old terrain. The ice front advances perhaps as much as a third of a mile per year.*



3 The Glacier Forms an End Moraine — *A warming climate halts the glacier advance across the area, and the ice begins to melt as fast as it advances. The ice front (IF) is now stationary, or fluctuating in a narrow area, and the glacier is forming an end moraine.*

As the top of the glacier melts, some of the sediment that is mixed in the ice accumulates on top of the glacier. Some is carried by meltwater onto the sloping ice front (IF) and out on to the plain beyond. Some of the debris slips down the ice front in the mudflow (FL). Meltwater runs through the ice in a crevasse (C). A supraglacial stream (SS) drains the top of the ice, forming an outwash fan (OF). Moving ice has overridden an immobile part of the front on a shear plane (S). All but the top of a block of ice (B) is buried by outwash (O).

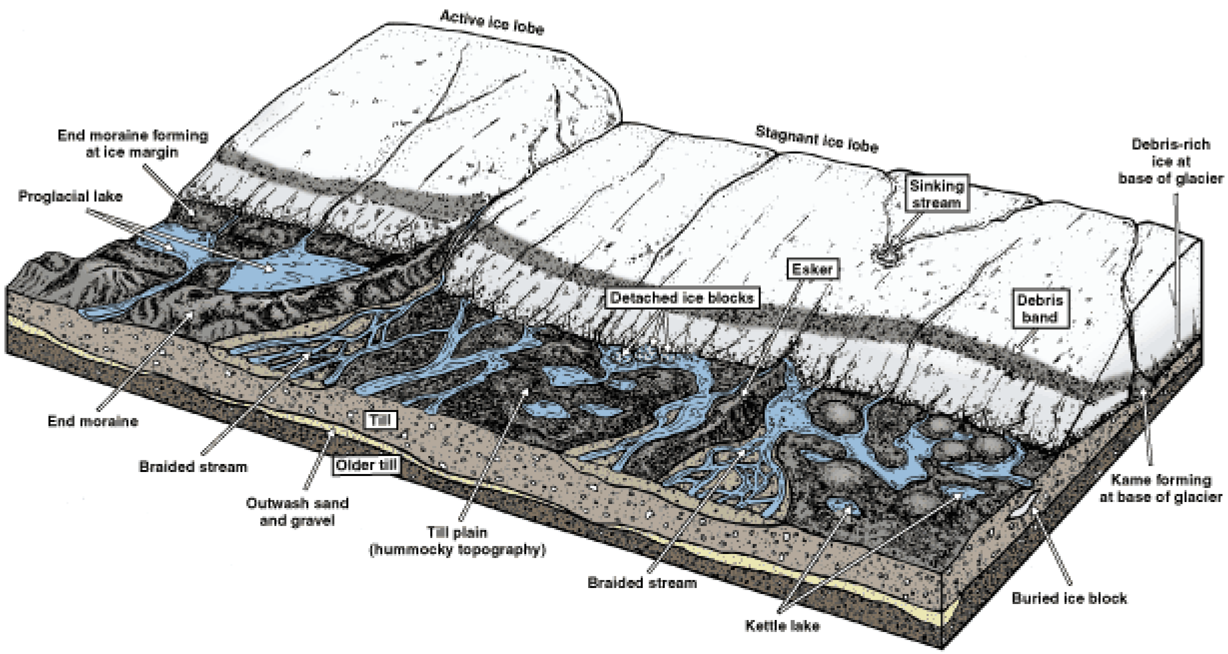
Sediment from the melted ice of the previous advance (figure 2) remains as a fill layer (T), part of which forms the till plain (TP). A shallow, marshy lake (L) fills a low place in the plain. Although largely filled with drift, the valley (V) remains a low spot in the terrain. As soon as the ice cover melts, meltwater drains down the valley, cutting it deeper. Later outwash partly refills the valley: the outwash deposit is called a valley train (VT). Wind blows dust (DT) off the dry floodplain. The dust will form a loess deposit when it settles. Sand dunes (D) form on the south and east sides of streams.



4 The Region after Glaciation — *As the climate warms further, the whole ice sheet melts, and glaciation ends. The end moraine (EM) is a low, broad ridge between the outwash plain (OP) and till plains (TP). Run-off from rains cuts stream valleys into its slopes. A stream flows through the end moraine along the channel cut by the meltwater that ran out of the crevasse in the glacier.*

Slopewash and vegetation are filling the shallow lake. The collapse of outwash into the cavity left when the ice block melted has formed a kettle (K). The outwash that filled a tunnel draining under the glacier is preserved in an esker (E). The hill of outwash left where meltwater dumped sand and gravel into a crevasse or other depression in the glacier or at its edge is a kame (KM). A few feet of loess covers the entire area but cannot be shown at this scale.

Continental Glacier



Time Table of Events in the Ice Age in Illinois

Years before present	Time-distance diagram Interglacial and glacial episodes	Sediment record	Dominant climate conditions Dominant land-forming and soil-forming events
HOLO-CENE	interglacial episode	River, lake wind, and slope deposits.	Warm; stable landscape conditions. Formation of modern soil; running water, lake, wind, and slope processes.
10,000	WISCONSIN (late) glacial episode; glacial ice	Till and ice-marginal deposits; outwash and glacial lake deposits; loess.	Cold; unstable landscape conditions. Glacial deposition, erosion, and land-forming processes (e.g., formation of end moraines, outwash plains, valley trains, proglacial lakes, kettles), plus running water, lake, wind, and slope processes
25,000	WISCONSIN (early and middle) glacial margin north of Illinois	Loess; river, lake, and slope deposits.	Cool; stable. Weathering, soil formation (Farmdale Soil and minor soils); wind and running water processes.
75,000	SANGAMON interglacial episode	River, lake, wind, and slope deposits.	Warm; stable. Weathering, soil formation (Sangamon Geosol); running water, lake, wind, and slope processes.
125,000	ILLINOIS glacial episode	Till and ice-marginal deposits; outwash and glacial lake deposits; loess	Cold; unstable. Glacial deposition, erosion, and land-forming processes, plus proglacial running water, lake, wind, and slope processes; possible minor soil formation.
300,000	YARMOUTH interglacial episode	River, lake, wind, and slope deposits.	Warm; stable. Long weathering interval with deep soil formation (Yarmouth Geosol); running water, lake, wind, and slope processes.
425,000 – 1,600,000 and older	? PRE-ILLINOIS glacial and ? interglacial episodes	Till and ice-marginal deposits; outwash and glacial lake deposits; loess plus nonglacial river, lake, wind, and slope deposits.	Alternating stable and unstable intervals of uncertain duration. Glacial deposition, erosion, and land-forming processes, plus proglacial and interglacial running water, lake, wind, and slope processes; interglacial weathering and soil formation.

PLEISTOCENE EPOCH (not to scale)

Source: https://www.isgs.illinois.edu/outreach/geology-resources/quaternary-glaciations-illinois

4.0 The Process of Soil Formation

4.1 Introduction

As you look at the soils around you, do you ever wonder where soils come from and why one soil is different than another? What natural forces act upon soils and what are the effects of these actions?

Pedology is the study of the formation and evolution of soil and the processes by which it is created. The formation of soils can be seen as a combination of the products of weathering, of structural development of the soil, of differentiation of that structure into horizons or layers, and finally, of its movement or translocation.

The journey of soil formation and evolution always begins from rocks. Rocks that form different soils are referred to as **parent material**. The chemical and physical properties of the parent rock are reflected in the characteristics of the soil. If the parent material is directly below the soil, it is the bedrock. However, the rock or parent materials that create different bodies of soils could have been transported great distances by forces of wind, water, or glaciers.

The formation of soil from rock can take thousands of years as natural forces such as physical and chemical weathering attempt to break down and modify the parent material. **Regolith** is the term used to describe the unconsolidated rock that has been physically and chemically modified. It is the transition stage from rock to soil. From this stage, the regolith is further evolved before mature soils are obtained.

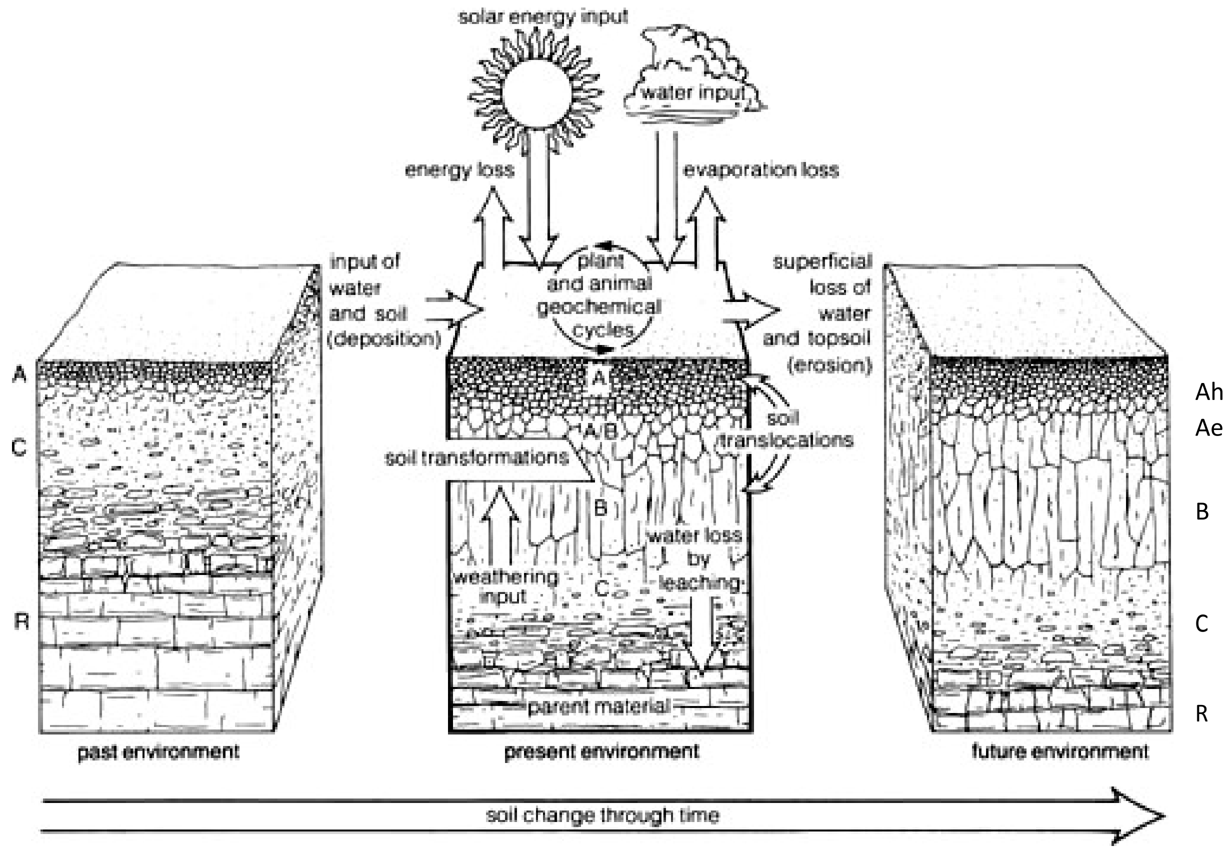


Figure 1: The evolution of soil from past to future (adapted from University of Arizona, 2007)

4.2 The Rock Cycle

If we examine the soil cycle carefully, we will realize that it is intimately connected with the rock cycle in a system that creates, destroys, and recreates rocks from soils, and soils from rocks.

Rocks are commonly classified as **igneous**, **sedimentary**, and **metamorphic**. The rock cycle does not necessarily start at any one of these three stages or proceed at any specific order. Rather, it can go from any one stage to any other and back. For example, any igneous rock can be transformed into a metamorphic rock, a sedimentary rock, or even into another igneous rock.

To understand how rocks form and transform, it is important to have a basic understanding of **plate tectonics**. Studies of the rock cycle have revealed that much of the driving force behind this process lies at the bottom of the oceans. Examining the ocean floor reveals diverging of the crust at mid-oceanic ridges; where constant volcanic eruption forms new crust and pushes the older crust outwards. The oceanic plate is forced away from the spreading ridge towards the continents. Where the oceanic and continental plates meet and collide, the older and heavier oceanic crust is forced beneath the lighter continent. This is called the **subduction zone**. Mountains are formed at the edge of the continent due to the intensity of colliding plates. The oceanic plate travels deeper and deeper beneath the ground, where high temperature and pressure cause melting of the crust. This is the basis for the formation of igneous rocks.

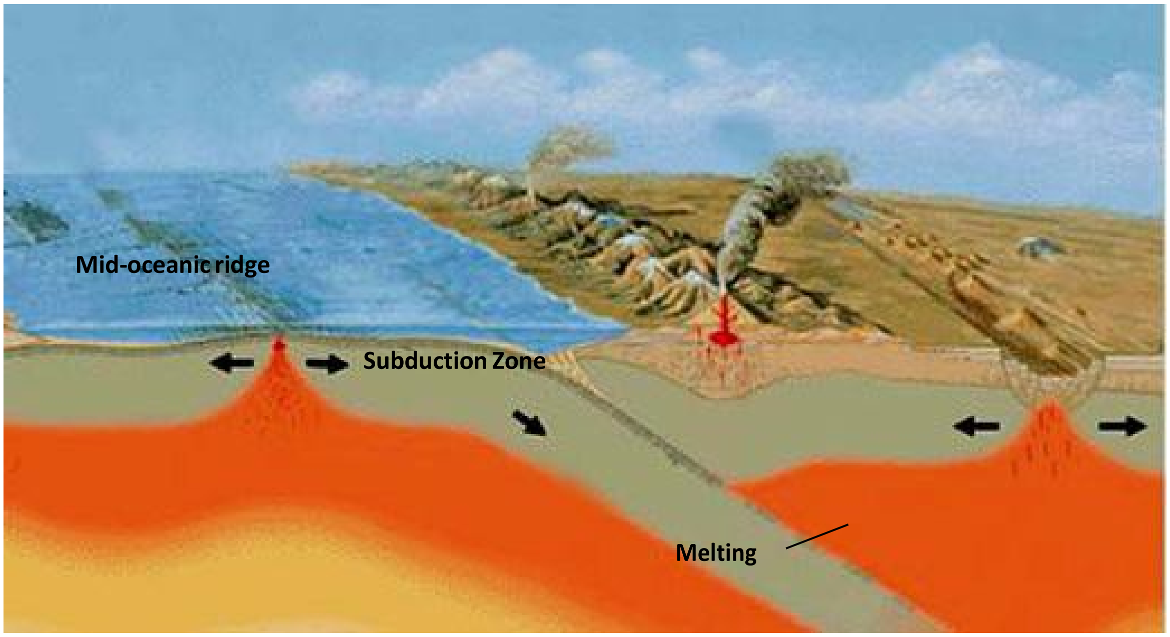


Figure 2: As new crust is produced at the mid-oceanic ridge, older crust is pushed outwards towards the continental crust. When oceanic and continental plates collide, the heavier ocean plates dive below at the subduction zone. High temperatures of the earth's interior cause melting of the subducting crust (Simon Fraser University, n.d.)

The word igneous means "born of fire". This is appropriately chosen considering that igneous rocks form from molten magma – rock that has been liquefied under the intense temperature and pressure of the earth's internal conditions. Temperatures of molten rock inside the Earth's mantle can reach as high as 1600 degrees C! Intense heating causes liquid magma to rise within the volcanic chamber. As the magma rises towards the surface of the earth, it begins to cool and crystallize. Some magma cools and solidifies before it even reaches the surface, forming **intrusive** or **plutonic** igneous rocks. The remaining magma continues to rise until it penetrates through the surface of the earth. The pressure of rising magma causes it to erupt, often violently, at the volcano's mouth. The magma above the surface of the earth, called **lava**, solidifies rapidly as it comes in contact with much cooler air or water. The result is the formation of **extrusive** igneous rocks.

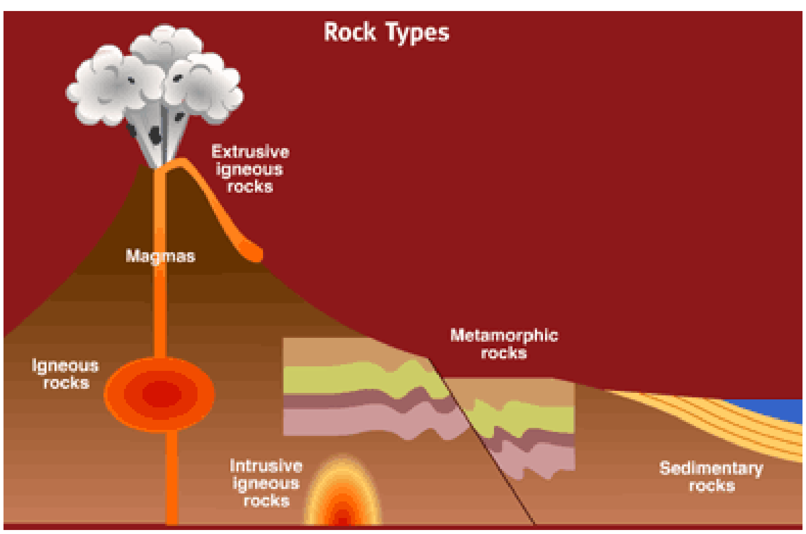


Figure 3: When magma cools beneath the surface of the Earth, intrusive or plutonic igneous rocks are form. Extrusive igneous rocks forms from the rapid cooling of lava above the surface of the Earth (Open Learn, 2006)

Exposed at the surface of the earth, these rocks are vulnerable to the processes of weathering and erosion. Weathering breaks the rocks down to smaller fragments and erosion by wind, water, and ice carries fragments from their original location. The loose materials accumulate and are buried by more sediment. Eventually, the loose particles of clay, silt, sand, or gravel become fused together with a cementing agent and form sedimentary rocks. This process of compaction and cementation of unconsolidated sediments into sedimentary rocks is called **lithification**. **Clastic** sedimentary rocks form from the binding of small rock fragments. **Biogenic** sedimentary rocks occur when the remains of living organisms, such as broken bones and shells, become lithified. **Precipitate** sedimentary rocks occur as a result of the evaporation of seawater and formation of precipitated salt rocks.

When sedimentary or igneous rocks become buried deep below the Earth's surface, they experience changes in their temperature, pressure, and chemical conditions that cause them to metamorphose. In other words, over millions of years, the rocks experience changes in their physical and chemical characteristics without melting, to form different rocks, called metamorphic rocks. Metamorphic rocks often occur in mountain belts where two continental plates collide, causing an extreme compressional force. The pressure of collision acts on the existing rocks, leading to regional metamorphism. Another form of metamorphism occurs in close proximity to intrusive igneous rocks, where radiated heat causes recrystallization of existing rock by means of contact metamorphism. Dynamic metamorphism occurs when two plates slide past each other. The heat generated by the frictional forces crushes and grinds the rock into metamorphic rock.

In time, igneous, sedimentary, and metamorphic rocks become exposed to the surface of the earth at lower pressure, lower temperatures, water, and vegetation. Unable to tolerate the new environmental conditions, different from those under which they were formed, rocks become unstable and begin to decompose into inorganic mineral matter that forms soil. This is when the process of soil formation comes into action.

4.3 From Rock to Soil

Bedrock begins to disintegrate into progressively smaller particles through a process called **weathering**. This is the first step towards soil formation. Chemical, physical, and biological actions help to facilitate the process of weathering.

Weathering is considered in terms of physical action and chemical action. In **physical weathering**, solid rock is broken into smaller constituents as a result of interaction with atmospheric conditions such as ice, water, heat, and pressure while maintaining the same chemistry. Physical weathering helps increase the exposed surface area of rock to help accelerate further weathering processes and soil formation. **Chemical weathering** occurs when rock is broken down by chemical reactions such as carbonation, hydrolysis or oxidation.

4.4 The Principle Soil-Forming Factors

Following the accumulation of soil from chemical and physical weathering, the loose material continues to mature and stabilize. Five factors collectively bring about the natural transformation of lifeless mineral matter into the rich, life-sustaining substance we know as soil. The different kinds of soils that are ultimately formed can be attributed to the quantity and quality of these factors. Soil scientists call these the factors of soil formation.

Parent material, climate, relief, organisms, and time are the 5 factors that exert their influences to give soil profiles their distinctive characters. Understanding the five soil forming factors helps us better understand why soils differ from place to place, how they contribute to the existence of different global environments, and how they can best be managed to maximize productivity.

4.4.1 Climate

Variation in **climate** has a primary influence on soil formation and properties. Climate refers to the specific temperature and precipitation regime as well as humidity, sunshine, and wind velocity. Climate is significant to the process of soil formation because it provides the energy that drives physical, chemical, and biological reactions on the parent material.

Perhaps the two most significant climate variables are temperature and moisture. Temperature and precipitation regimes directly impact with the type and rate of physical and chemical weathering processes mentioned in the previous section. As temperature and precipitation increase, so does the rate of weathering, the frequency and magnitude of soil chemical reaction, and the rate of plant growth. Temperature controls the rate of biological activity by soil organisms, while moisture influences soil pH and the rate of decomposition of organic matter. Precipitation also affects horizon development or layering through leaching and the translocation of sediments within the soil profile.

4.4.2 Organisms

Soil organisms are responsible for aiding the process of organic matter accumulation and conversion of organic nutrients into mineral matter that can be taken up by plants. Soil organisms also help in profile differentiation and mixing.

Vegetation such as plants, shrubs, and trees, help protect the upper layer of the soil against the harsh impacts of erosion by providing a protective cover that reduces the speed of wind and water. Vegetation can help in slowing the rate of runoff and wearing away of fertile soil. Plants also accelerate the rate of physical and chemical weathering by pushing rocks apart with their roots and releasing organic exudates that decompose rocks and release nutrients necessary for growth. Vegetation can also prevent water from evaporating at the surface of the soil. Evaporation of water at the soil surface can sometimes lead to the accumulation of salts in the root zone of plants that hinders water uptake. The moisture regime of the soil can impact the type of biotic environment that exists in different regions of the world.

When plants shed their leaves, or when they die, they leave behind organic matter that increases the structural stability of the soil aggregates and provides nutrients for the growth of other plants. Organic matter also increases moisture and cation-holding capacity.

Soil organisms also play a crucial role in soil formation. **Decomposers** within the soil help to recycle organic matter left by dead organisms to nutrient forms that are available to plants. Fungi, for example, consume leaf-litter and accelerate the process of decay. Bacteria capture nitrogen from the air and incorporate it into the soil to be used by plants. Earthworms and small mammals burrow, mix, and further incorporate organic matter into the soil. Overall, soil organisms add humus and nutrients to the soil, necessary for healthy soil functions such soil structure and fertility.

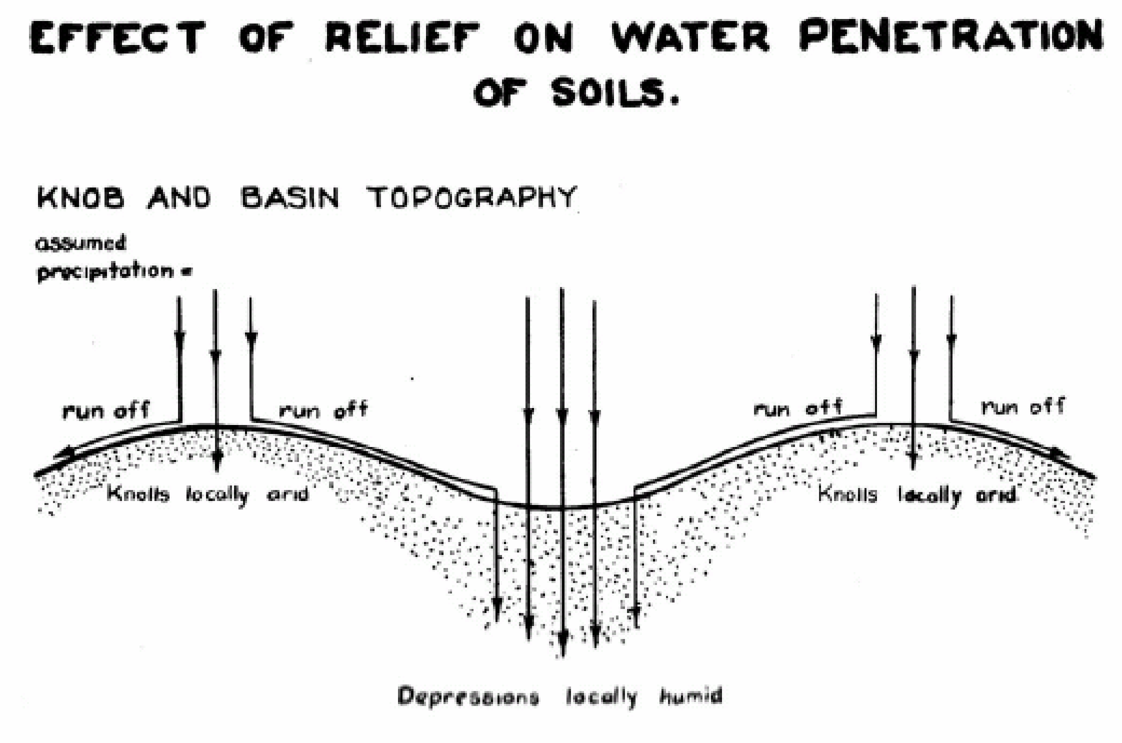


Figure 4: Impact of topography on microclimate can be seen when analyzing knolls and depressions. Hills maintain less moisture as rainfall and runoff collect in depressions (Pennock, 2006)

4.4.3 Relief

Relief, or topography, refers to the configuration of land in terms of its altitude and slope degree. Topography can modify the microclimate and drainage ability of soil at a regional or local scale, and controls the type and rate of soil formation.

In the Northern Hemisphere, south-facing slopes receive greater exposure to sun and therefore experience warmer and drier microclimates than their north-facing counterparts. In the Southern Hemisphere, this is true for north-facing slopes. In comparing south and north-facing slopes, you will find major differences in the types of ecosystems that can be supported by each. Soil formation also differs on the two sides of a slope in terms of depth, texture, biological activity, and soil profile development.

Furthermore, the degree of a slope affects the rate of erosion and moisture accumulation. Steeper slopes are more prone to landslides and natural erosion due to gravity. Precipitation is much more likely to wash away topsoil on steeper lands such as mountains than on flat country such as the prairies. Consequently, steeper topography inhibits the accumulation and development of soil due to continual removal of surface sediments.

In addition, the nature of soils found in valleys differs from that on uplands due to drainage of water. Depressions are locally humid and knolls are locally arid. During and after precipitation, water flows down the slope and gathers at the bottom of the valleys. As a result, hill and mountaintops are much better drained than soils in depressions. Good drainage enhances the development of soil horizons through translocation of soil particles. Therefore, soils that are well drained are generally more mature.

Figure 5: The north-facing slope on the left receives less exposure to sunlight throughout the year and maintains a moister and cooler microclimate than the south-facing slope on the right. Weather occurs at different rates on each side of the slope. (Wikipedia, 2015a)

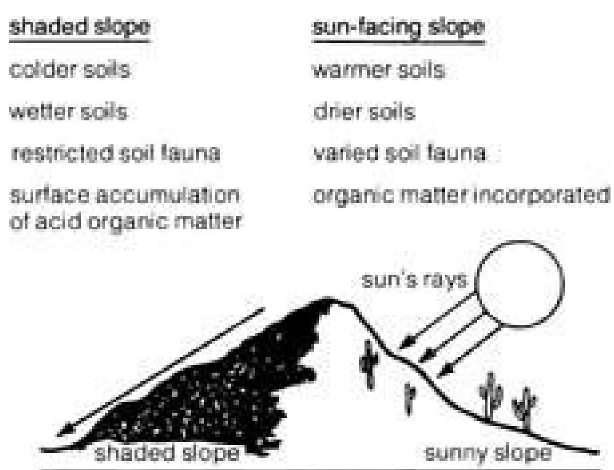


Figure 6: Effects aspect on soils (University of Arizona, 2007)

4.4.4 Parent Material

Parent material refers to the unconsolidated material including igneous, metamorphic, or sedimentary rocks, in addition to other organic and mineral materials from which soils were developed. Parent material may be directly beneath the soil, in which case it is referred to as bedrock or it may have been transported to an area by erosive forces of wind, water, or glaciers.

The type of parent material influences the rate of soil formation, since some rocks break down much faster than others. The properties of parent material can also determine the mineral composition and physical and chemical attributes of the soil. For example, soils formed from limestone are rich in minerals important to plant growth, while those derived from granite tend to be poor in essential nutrients required for a healthy plant life cycle.

Texture, water-holding capacity, **acidity**, and **fertility** are also soil properties that are inherited from the parent material. Soil texture, a property of the parent material, affects the rate of downward water movement, thereby affecting translocation of nutrients and soil particles. The chemical makeup of parent material also affects **pH** and nutrient availability. Calcitic and dolomitic parent materials form alkaline soils that favor the availability of certain nutrients.

4.4.5 Time

The impacts of climate, organisms, relief, and parent materials are dynamic through time. A great length of time is needed for these factors to interact and produce soils from rocks. It can take thousands of years for a few centimeters of soil to develop from parent rock. Older soils are more mature and have better defined horizons than younger, immature soils. Younger soils may be less deep with a lower concentration of organic matter.

It is important to realize that the five factors of soil formation do not occur independently of one another. Rather, they are interrelated forces that collaborate to augment and further advance the impacts of the others. In the end, soils reflect the integrated work of the specific climate, biological activity, time range, parent material, and topography that helped form them.

4.5 Structural Differentiation

Over time, soils begin to differentiate vertically and display distinct horizons. A **horizon** is a specific layer in the soil that runs parallel to the ground surface and entails different properties from horizons above and below. Soil horizons vary in terms of color, texture, and structure. Though each soil has at least one horizon, the more mature a soil is, the more differentiated its horizons are.

Soil horizons evolve with the addition*,* loss*,* **translocation**, and **transformation** of soil particles. Additions include organic matter, water, air, and energy from the sun. Soils losses include the evaporation of water, leaching of nutrients, or erosion. Translocation refers to the movement of soil-forming material up and down the **soil profile**. The soil profile consists of the combined sequence of all the horizons in a soil. Rainwater percolates down the soil profile due to gravity, transferring some materials from the upper part of the soil to lower portions. Burrowing animals further mix and move materials within the soil. The formation of arrangement of soil components into structural aggregates is called transformation.

Horizon formation is a function of the **biogeochemical** factors that influence soils over a long period of time (i.e. climate, organisms, parent material, topography, time). The type and sequence of the horizons that make up each body of soil are characteristics that help to classify them. In Canada, the horizons are identified with capital letters: L, F, H, A, B and C.

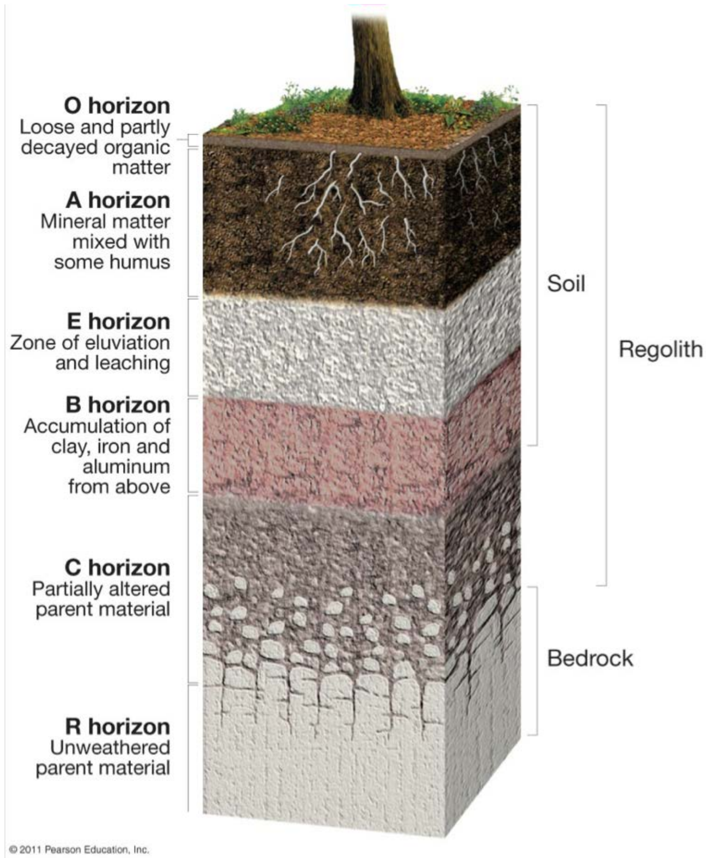


Figure 7: A simplified soil profile showing the designations used in Canada, thus L, F, and H, A, B and C horizons. Any given soil may have some or all of the seen horizons at varying depths (BC Ministry of Environment, 2015)

4.5.1 O Horizon

The organic horizon lies on the uppermost layer above the soil. Organic matter is generally distinguished by its dark color. This horizon is nourished by the addition of dead vegetation and organisms that are at various stages of decay. Less decayed organic matter lies above the more decomposed organic humus.

In well aerated environments leaves, needles, twigs and branches fall to the earth, accumulate and begin to decompose on top of the mineral soil. The level of decay is the criterion for distinguishing the subdivisions Oa, Oe and Oi. The Oa subdivision represents slightly decayed organic materials ; Oe is intermediately decomposed; and Oi is the most decomposed layer that can no longer be attributed to the original material that made it. Not all soils are endowed with an organic horizon. It usually exists only on soils that are permanently covered by vegetation. Those soils that do have an organic layer are subject to decreasing levels of organic matter down the soil profile. The O horizon is dark because decomposition is producing humus.

4.5.2 A Horizon

The A horizon lies beneath the organic layer. In some soils the A horizon is higher in organic matter compared to the layers below due to the downward movement of organic material from the O horizon and is therefore darker in color. In other soils this horizon experiences leaching or eluviation of organic matter, minerals and nutrients with the downward movement of water and this is expressed by a lightening of the soil color. The A horizon is also the zone where most biological activity occurs. Worms, nematodes, fungi, bacteria, and most plant roots are active in this horizon. Together, the A and O horizons constitute the topsoil. **Topsoil** is the portion of the soil that acts as a growth medium for vegetation, providing humans and other animals with the food and a wild habitat. A horizon may be referred to as a surface layer in a soil survey. An A horizon that has been buried beneath more recent deposits is designated as Ab.

4.5.3 E Horizon

The B horizon is the layer above the C horizon and below A horizons. The B horizon is where the materials accumulate that are translocated from the upper portion of the soil profile. For example, the organic matter, fine clay and mineral matter that were leached with water from the horizons above, are deposited in the B horizon. This is also called the zone of illuviation. There is a close relationship between the A and B horizons. Translocations as well as many biological and chemical reactions take place between them. The main feature of this horizon is the loss of silicate clay, Iron, aluminum, humus or some combination of these, leaving a concentration of sand and silt particles.

4.5.4 B Horizon

Below the A or E horizon is the B horizon, or subsoil. The B horizon is usually lighter colored, denser, and lower in organic matter than the A horizon. It commonly is the zone where leached materials accumulate. The B horizon is further defined by the materials that make up the accumulation, such as the letter t in the designation Bt, which identifies that clay has accumulated. Other illuvial concentrations or accumulations include Iron, aluminum, humus, carbonates, gypsum, or silica. Soil not having recognizable concentrations within B horizons but showing a color or structural difference from adjacent horizons is designated Bw.

4.5.5 C Horizon

The C horizon or substratum. Partially disintegrated parent material and mineral particles are in this horizon. This layer is the transition stage between bedrock and soil and is least affected by soil-forming processes. In very young soils that do not yet have defined horizons, the entire profile of the soil is called the C horizon. Some soils have a soft bedrock horizon that is given the designation Cr. C horizons described as 2C consist of different material, usually of an older age than horizons which overlie it. There is very little organic material found in this layer and plant roots do not generally penetrate into the C horizon.

4.5.6 R Horizon

The lowest horizon, the R horizon, is bedrock. Bedrock can be within a few inches of the surface or many feet below the surface. Where bedrock is very deep and below normal depths of observation, an R horizon is not described.

Horizons Source: https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/edu/7thru12/?cid=nrcseprd885606#horizons

Lowercase letters denote the distinctions of these horizons.

Not all soils have all of the mentioned horizons. Soil horizons also vary in terms of depth, composition, and structure. Newly formed soils are shallower and have less differentiated horizons, while the profile of mature soils may display the full set of horizons. The specific depth, chemical composition, and structure of soils and their horizons at a given time are a direct result of the factors that influenced their formation.

4.6 Soil Classification

Understanding the properties of horizons and the distinguishing characteristics of the soil profile has allowed soil scientists to classify soils into different categories. This is called soil **taxonomy**. The ability to classify soils allows scientists to recall knowledge in a systematic manner and communicate information in a consistent manner with other scientists. Soil classification makes it simpler to understand the relationships among different soils and their environments and to implement appropriate management techniques.

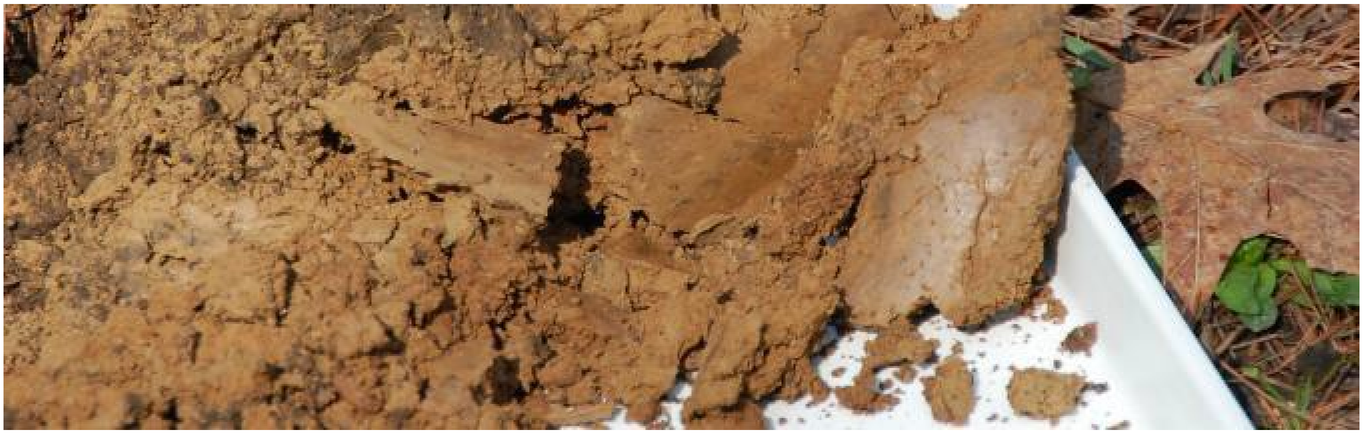
The classification of soils is not an easy task. This is because unlike plants and animals, soils are not individual entities. Rather, soil is a continuous body that gradually transforms from one type of soil to another. There is no defined beginning and end to any body of soil. Also, different countries have different systems for soil classification.

In Canada, the soil classification scheme is a comprehensive system based on the properties and arrangement of horizons which are products of the soil forming environment. These diagnostic properties are relatively stable and do not change significantly through time. Canadian soils have been categories into five main hierarchal levels that divide and subdivide into more specific clusters. Soil orders are the highest level and the most general grouping. There are ten main orders to Canadian soils. They are: luvisols, podzols, brunisols, regosols, cryosols, chernozems, gleysols, vertisols, organic, and solonetzic soils. Each order is further divided by great group, subgroup, family and series. Series is the most specific division.

(See Soil Classification Guide PDF on website to study Classifications)

Orders	There are 12 orders. They are differentiated by the presence or absence of diagnostic horizons or features that reflect soilforming processes.
Sub order	Sixty-four suborders currently are recognized. The differentiae for the suborders vary with the order. The differentiae used in defining the suborders of Alfisols include important properties that influence genesis and that are extremely important to plant growth. The differentiae in six of the other orders closely parallel those of Alfisols. In the remaining orders, differentiae were selected to reflect what seemed to be the most important variables within the orders.
Great group	There are more than 300 great groups. Differentiae in the great group category segregate soils that have the following properties in common: **Close similarities in kind, arrangement, and degree of expression of horizons**.—Exceptions are made for some thin surface horizons that would be mixed by plowing or lost by erosion and for horizons that indicate transitions to other great groups.
Sub group	There are more than 2,400 subgroups. Through the categories of order, suborder, and great group, emphasis has been placed on features or processes that appear to dominate the course or degree of soil development. In addition to these dominant features, many soils have properties that, although apparently subordinate, are still markers of important sets of processes.
Family	In this category, the intent has been to group the soils within a subgroup having similar physical and chemical properties that affect their responses to management and manipulation for use.
Series	More than 19,000 series have been recognized in the United States. The differentiae used for series generally are the same as those used for classes in other categories, but the range permitted for one or more properties is narrower than the range permitted in a family or in some other higher category.

Source: https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_051232.pd



5.0 The Physical Nature of Soils

The term 'fertile' usually describes a soil that is rich in essential nutrients, necessary for plant growth. Though many people associate fertility with the ability to support growth, not all fertile soils are productive soils. There are a wide range of physical factors that contribute to the soil's ability to support vegetative growth. The physical nature of soil is among the key properties that determines the suitability of land for a particular practice.

Physical properties are those that can be quantified and described with measurements such as length, volume, mass, and temperature. Soil physical characteristics determine if a soil is strong enough to withstand the weight of traffic or if it is weak and will collapse under stress; if a soil can hold large amounts of water for plant use or if it is easily leached. Agriculture and engineering depend heavily on the soil's physical capabilities. The physical structure of any given soil has been derived from the impacts of the vegetation, topography, and climate on the parent material over time. Any minor change in these five factors can create a soil with very different physical properties. This is why soil properties can vary widely from one place to another. Not all soils are fitting for the same practices and applications as other soils. Therefore, it is important to have a thorough understanding of the physical properties of soils and their impact on soil functions.

5.1 Four Major Soil Components

Any body of soil is comprised of four major constituents – mineral matter, organic matter, air and water in three different phases – the liquid phase, the solid phase, and the gas phase. Different bodies of soils vary in the proportion of the components that make up the soil. Ideally, the solid phase contributes approximately 50% by volume to the soil. This solid phase is divided into the inorganic mineral matter and organic matter. The remaining 50% of the soil volume is pore space. This is the open space in between the solid particles that is occupied by air and water. The liquid and gas phases each contribute approximately 25% to the total volume but fluctuate according to soil wetting and drying cycles.

It is important to note that the composition of subsoil deeper beneath the surface of the earth is slightly different from that of topsoil. Due to increased pressure, subsoils tend to be more compact and are thus lower in pore space. Pore space in the subsoil is generally smaller in size and is dominated by water, which seeps down the soil profile due to gravity. Also, subsoil contains less organic matter than its topsoil counterpart.

These four major soil components – mineral matter, organic matter, air, and water – interactively create the framework, which determines the properties of soils as a natural system. The volume composition of soil is what determines its suitability for plant growth and activity of soil organisms.

5.1.1 Inorganic Mineral Matter

For an average mineral soil, 45% of the soil is composed of mineral matter. Mineral matter refers to the inorganic portion of the soil that is derived from the physical and chemical weathering of original parent rock into regolith (weathered parent material), and subsequently, into soil. Consequently, the mineral composition and properties of the mineral matter such as pH and texture is reflective of the parent rock from which it was derived.

The size and abundance of mineral particles in soil is extremely variable and contributes greatly to the properties of each soil. Mineral particles, divided by size, are categorized as **rock, gravel**, **sand**, **silt**, and **clay**.

CLAY

The scientists have assigned the name *clay* to the finest particles and not without reason. Clay size particles are the source of most of the chemical properties of soil. They are responsible for the retention of many of the plant nutrients in the soil, such as calcium, magnesium, potassium, trace elements and some of the phosphorus. Clays react with the breakdown products of organic matter to stabilize the humus in the soil. A soil without clay particles can be a very infertile soil. Clays, because of their very small size and very large surface area, are able to retain greater amounts of water than sandy soils. On the other hand, as will be discussed in a latter article, clays hold the water more closely and do not release the water as readily to grass roots as sands. Clay particles have a vastly greater tendency to stick together than sand, thus it is common farmer knowledge that soils high in clay are difficult to till. When a small sample of a clay soil is wetted and rubbed between the fingers it will feel very sticky and is easily formed into a string.

SILT

The particles classified as *silt* are intermediate in size and chemical and physical properties between clay and sand. The silt particles have limited ability to retain plant nutrients, or to release them to the soil solution for plant uptake. Silt tends to have a spherical shape, giving a high silt soil a soapy or slippery feeling when rubbed between the fingers when wet and is more difficult to form into a string than clays.
Because of the spherical shape, silt also retains a large amount of water, but it releases the water readily to plants. While silt soils are generally considered very fertile for the growth of plants, largely due to their water characteristics and ease of cultivation, engineers dread working with them due to their relatively easy release of water and lack of ability for the particles to stick together.

SAND

Sand particles are essentially small rock fragments, and as such, have little or no ability to supply grass with nutrients or to retain them against leaching. As rock fragments, sandy soils feel gritty between the fingers. The sand grains have little ability to stick together; thus sandy soils cannot be rolled into a string when wetted. It is well known that sandy soils are droughty soils because they retain little water when wetted. Nevertheless what water is retained is released to plants easily. When rain or irrigation occurs the water readily penetrates the soil surface, the excess moves through rapidly and the soil remains well aerated. These properties make sands a desirable medium for growing sports turf where there is no limitation in applying water and nutrition, as needed, throughout the season.

SOIL COMPONENT	PARTICLE DIAMETER
Rock	Greater than 75.0 mm
Gravel	2.0 to 75.0 mm
Sand	0.05 mm to 2.0 mm
Silt	0.002 to 0.05 mm
Clay	Less than 0.002 mm

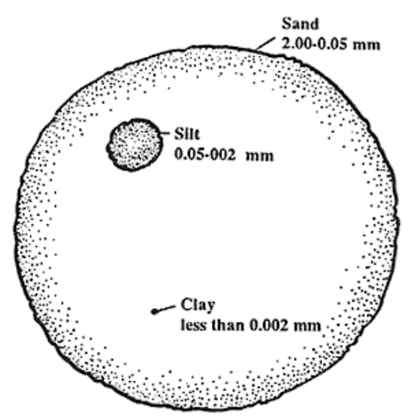


Figure 8: Relative size of sand, silt, and clay particles. (Outside Pride, 2015)

5.1.2 Organic Matter

Organic Matter is derived mainly from dead and decaying plant and animal material that have accumulated at or near the soil surface and are continually broken down with the aid of living soil organisms. Organic matter accumulates in the topsoil and decreases in concentration down the soil profile.

For an average mineral soil contents of organic matter typically range from 1-5% by volume. Soils high in organic matter can be identified by their darker color.

The presence of organic matter is crucial to the health and productivity of soil. Organic matter assists in the binding of soil into aggregates, improves soil structure, allows roots to penetrate through the soil, and helps to increase water-holding capacity. Furthermore, organic matter is a major source of essential nutrients such as nitrogen, potassium and sulphur (N, P, S), and provides energy for soil organisms. Humus, the decay-resistant portion of organic matter, remarkably exceeds clays in water and nutrient holding capacity.

5.1.3 Water

Water generally occupies one half of the soil's pore space, constituting up to 25% of the soil's total volume. The size distribution of soil pores determines the ease with which plants may take up water molecules. Water is held to the surface of solid matter with varying degrees of tension depending on the size of pores and the quantity of water content. Water in the largest pores (macropores) is most effortlessly absorbed by plants. This is called *available* water. As the water from the largest pores is taken up, it becomes increasingly difficult and more energy-intensive for plants to uptake water and dissolved nutrients. Water contained in tiny pores (micropores) and thin films is held tightly to the surface of soil particles and is not easily released for plant uptake. The *wilting* point is reached when the soil water can no longer be extracted for plant use. The wilting point is reached at higher water content in clays compared to sands, due to the presence of a much larger proportion of smaller pores in clays .

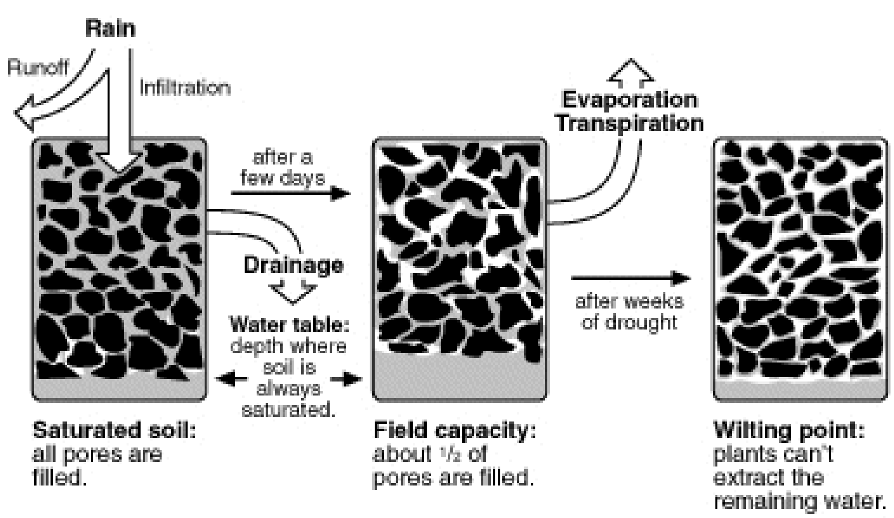


Figure 9: At wilting point, soil water is only contained in micropores and thin films around soil particles. This water is heldtightly that plants are unable to extract the water and therefore wilt (University of Minnesota, 2001)

Soil water is essential for the growth of plants as it provides not only the liquid to quench their thirst, but also the nutrient elements required for growth and reproduction. Soil water is the transport medium for essential nutrients. Nutrients are taken up by plants by three basic mechanisms: root interception, mass flow, and diffusion.

Only a very small and insignificant portion of the plant's nutrient requirements are sustained through root interception. In this case, the nutrients are taken up directly from the soil solids. The second and most important mechanism of nutrient uptake is mass flow. Mass flow occurs when nutrients enter the roots zone of plants and are absorbed along with water. Nutrient uptake through mass flow is highly influenced by moisture availability and soil physical properties mentioned in the previous paragraph. Finally, diffusion is the mechanism by which nutrients move down the concentration gradient, from an area of higher concentration to an area of lower concentration. The solubility and availability of nutrient ions is heavily impacted by the pH of soil solution, which is yet another important aspect of soil water to be considered.

5.1.4 Air

The gas component of soil serves the same purpose as the air in the atmosphere; it provides oxygen for living organisms to breath, and allows carbon dioxide from animal and root respiration to escape from the soil. Soil air differs from air in the atmosphere in that the composition of air in the atmosphere is much more uniform than soil air composition which varies significantly in different air pockets. This is because soil air flow is greatly restricted by soil solids and liquids.

Furthermore, soil air has a significantly higher relative humidity (moisture content) that may reach up to 100% in ideal conditions. Also, soil air contains carbon dioxide concentrations that are several hundred times higher than that in the atmosphere, and oxygen concentrations that are much lower. Soil organisms take up oxygen from the air pockets, and release carbon dioxide from respiration. Since air flow between the atmosphere and the soil is very slow, the gaseous composition of soil and air are never the same. In soils with a large proportion of small pores, water usually dominates the pore spaces, preventing optimum aeration for plant growth and microbial activity. Carbon dioxide concentrations are generally high, and oxygen levels low, as water limits air flow and inhibits equilibrium between the atmosphere and the soil.

5.2 Soil Texture

The texture of soils is determined by the relative proportion of each of the three particle sizes (sand, silt, clay) that are found in a sample of soil. Soils that are dominated by clays are termed **fine-textured** soils while those dominated by sands are referred to as *coarse-textured* soils. Texture is a basic property of soil, in that it is static through time and is not easily subject to change.

Soil science professionals categorize soils into different soil textural classes based on similarities in particle size distribution. The range of each class is selected to represent textures with similar properties and is named to identify the dominant particle sizes. Soils with a moderate mix of the three particle sizes are called **loams**.

A soil **texture triangle** is used to visually display the different soil textural classes by the percentage of sand, silt, and clay. The different sides of the triangle represent the percentage of each soil particle size present in a sample of soil. The intersection of the three sizes inside the triangle represents the texture class, which is bounded by bolded lines. To read the percentage of clay, you use the axes that run horizontally; sand, the axes that run from lower right to upper left; and silt, the axes that run from upper right to lower left across the triangle.

Soil texture has a strong influence on the physical and chemical properties of soil. Permeability, water retention, aeration, fertility, bulk density, and structure are all affected by the soil texture. Furthermore, clays have a greater ability to absorb and store nutrient ions for use by plants. As a result, clay soils are more fertile than sandy soils.

Water-holding capacity – the amount of water a soil can hold – is a function of soil texture. Fine-textured soils, such as clays, have a greater surface-area to volume ratio than coarse-textured sands. The greater surface area of clays allows for greater adhesion between water and solid components. In comparison, sands have large macropores with less surface area to adhere to water molecules. Water drains easily from macropores of sand, leaving air to replace the pores. This is why sands have great **permeability** and higher **aeration** than clays and silts. Soil textural class can be estimated fairly easily in the field using simple hand texturing tests that evaluate the relative proportions of each particle size in a soil sample. More accurate determinations of the percentages of sand, silt and clay can are determined in the laboratory using the Bouyoucos method which utilizes a hydrometer to measure the density of a soil-water suspension at a reference depth over a period of time. The suspension density decreases with the passage of time as the larger particles settle.

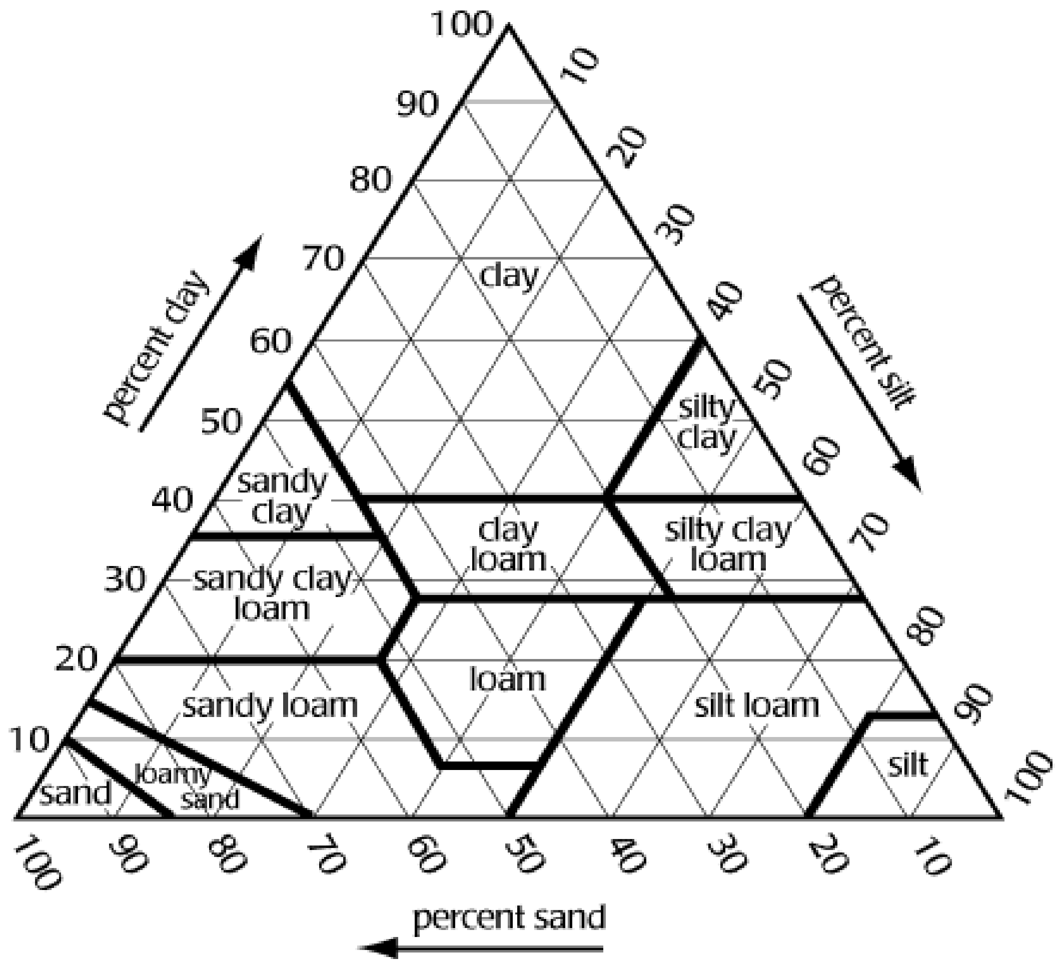


Figure 10: Soil Texture Triangle (Soil Genesis, n.d.)

A straight line drawn along the grid for the percentage clay and for the percentage silt will intersect within a class name are.

For Example: 19.0% clay 61.0% Silt and 20.0% Sand is a Silt Loam soil.

5.3 Soil Structure

If you look closely at soils, you will notice the binding of individual granules into larger units that are called aggregates or peds. Soil structure refers to the nature of the arrangement of particles into these aggregate forms. Structure is very important because it affects the stability of soil and its resistance to degradation and collapse under pressure. Addition of organic matter can help to increase stability of aggregates, while physical disturbances by wind, water, traffic, and tillage can break apart and weaken the soil structure.

Good structure generally means the presence of large pores between aggregates that provide conduits for soil organisms and permit the penetration of plant roots, water, and air. This increases the rate of water infiltration, water retention, aeration, and plant growth. Soils with stable aggregates are also less prone to surface erosion both because the soil particles are less likely to be detached from one another, and because of improved drainage.

Poor soil structure often refers to a soil that is compact and weak. Weak soils are prone to collapse under pressure of overlying buildings and roads. Unstable soil aggregates are easily moved or eroded by wind and water and deposited elsewhere, where they form hard crusts when they dry. Hard surface crusts prevent the emergence of seedlings, and encourage runoff, erosion, and less available water. Dense or poor structure reduces the movement of air, water, nutrients, and soil biota.

The formation of aggregates is influenced by texture, composition, and environment. Aggregation occurs when charged soil particles remain close together due to interactive forces such as hydrogen bonding, electrostatics, or van der waals forces. Aggregate formation is enhanced by biotic and abiotic factors that increase cementation. For example, organic matter can help cement aggregates to increase stability, and cycles of wetting/drying can decrease aggregation.

Aggregates are characterized by their size, shape, and strength. Some types of soil do not readily stick together to form stable and strong aggregates and are therefore structureless. You may have noticed this while attempting to build a sand castle on the beach. Sand particles easily fall apart into loose single grains. Some fine-textured clay soils are also structureless, forming dense and massive chunks that have no visible structure and are hard to break apart.

There are seven major classes of structure seen in soil. These are: single grain, massive, platy, prismatic, columnar, blocky, and granular,

Platy

Platy structured soils are made of flat, thin plates that are oriented horizontally. This type of structure is most commonly found in the subsurface of soils that have been compacted under pressure by animals and machinery. Platy structures usually hinder downward movement of water and penetration of plant roots through the soil.

Prismatic

Prismatic soil structures are characteristic of the subsoil and are formed when freezing/thawing or wetting/drying cause vertical cracks to develop in the soil. As the name indicates, prismatic structures have vertically extending surfaces with flat or round faces.

Columnar

Columnar structure is very similar to prismatic, with the distinction of each column having visible rounded tops with salt caps. Columnar structure is commonly found in arid climates. Growth of roots on columnar structured soils is rather slow and bound by the density of soil.

Blocky

As the name indicates, angular block-like or polyhedral units make up the blocky structure. This type of structure occurs commonly in soil with high clay content where swelling and shrinking of the clay causes cracks to develop.

Granular

The units of granular structure are composed of spherical or angular bodies that are comparable to cookie crumbs. This type of structure is commonly found in the surface-soil of areas with high organic matter content such as grasslands and highly amended gardens. Granular structures allow for good porosity and easy movement of air and water, and are very suitable for agriculture.

5.4 Bulk Density

Bulk density plays an important role in determining if soil has the necessary physical characteristics to support the foundation of buildings, plant growth and penetration of roots, and water infiltration. Bulk density is an indirect measure of pore space in the soil, which is primary impacted by soil texture and structure. It is calculated as the mass of dry soil solids divided by the total volume of soil (i.e. soil particles and pore space). It is measured in units of g/cm^3.

Soils that are porous, loose, and well-aggregated have lower bulk density than compacted and non-aggregated soils. In general, bulk density increases with increases in sand content and decreases in organic matter content. While sandy soils have larger average pore sizes than clay soils they contain lower overall pore space and therefore have higher bulk densities. Organic matter content is light in weight and also promotes aggregation of soil into peds, which leads to increase pore space and lower bulk density.

Figure 11: Shows a soil that has been compacted by heavy farming machinery. (OMAFRA, 2009)

The bulk density of the soil is not an intrinsic property, in that it is subject to change over time based on the management of the soil. Heavy traffic due to grazing of cattle or use of heavy machinery over a field asserts high pressure on the soil and can increase the bulk density of the soil. With an increase in bulk density, the soil becomes more compact and less pore space is available to provide plants and soil organisms with air and water. More compact soils inhibit water movement and reduce infiltration down the soil profile. Low permeability causes water to remain on the surface and increase runoff and erosion.

There are several ways of measuring and calculating the bulk density of soil. Perhaps the most common method is the core sample method. Using this method, the soil science professional pushes or hammers a metal cylinder of known volume (with two open ends) through the soil to obtain a core sample of the soil. The soil inside the core is extracted and oven dried to drive away any contained moisture. The weight of the oven-dried mass is divided by the volume of the cylinder to obtain the bulk density of the soil.

Figure 12: A metal core is used to collect soil core sample for bulk density measurements (University of Rhode Island, n.d)

5.5 Color

The color of the soil can reveal important details about the properties of soil and the processes operating in the soil profile. Color variation is a simple and useful way of differentiating between different soil horizons and orders specifically, color is indicative of three important facts about the soil: the state of aeration and drainage, the organic matter content, and the state of iron oxides.

Generally, moist soils and those with high organic matter appear darker in color. This is why the rich organic topsoil appears darker than subsoil. Red and brown soils are usually well drained and aerated, allowing aerobic organisms in the soil to remain active. Also, in well aerated soils, iron is oxidized more readily and develops a 'rusty' color. Gray and blue soils indicate an area of poor aeration due to poor drainage, prolonged saturation or waterlogging. The lack of oxygen means that the iron is in the reduced form, which gives soil its grey-blue color. Evidently, color can say much about the properties of soil. The table below summarizes some of the properties of the soil that can be deduced from different colors.

Condition	Dark (dark grey, brown to black)	Moderately Dark (brown to yellow brown)	Light (pale brown to yellow)
Organic matter	high	medium	low
Erosion factor	low	medium	high
Aeration	high	medium	low
Available Nitrogen	high	medium	low
Fertility	high	medium	low

Table 2. Properties of soil based on colors.

The color of soil is described in a standardized fashion using the notation from a Munsell Color Chart which recognizes color in terms of three dimensions: **hue**, **value**, and **chroma**. There are five principal hues: Red, Yellow, Green, Blue, and Purple, and five intermediate hues: Red-Yellow, Yellow-Green, Green-Blue, Blue-Purple, and Purple-Red. Value indicates the lightness of a color. The scale of value ranges from 0 for pure black to 10 for pure white. Finally, chroma describes the intensity of a color. Colors of low chroma values are sometimes called weak or pastel, while those of high chroma are said to be highly saturated, strong, or vivid (fluorescent). The scale starts at 0 for neutral colors and extends to infinity (there is no upper limit).

The Munsell notation is written as follow: Hue Value/Chroma. An example would be 7.5R 7/2. 7.5R refers to the color in the red hue, 7/ refers to the lightness, and /2 indicates the chroma.

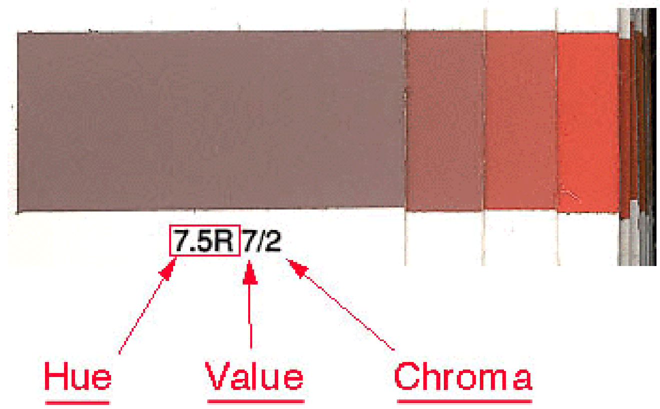


Figure 13: Munsell notation (USGS, 2015)

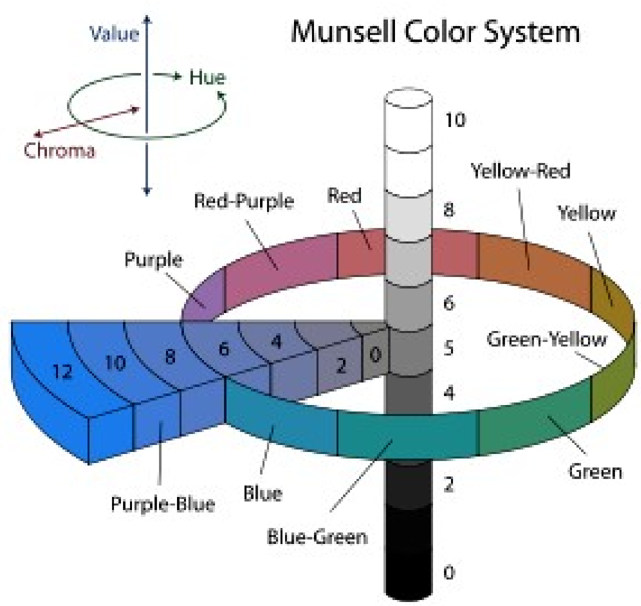
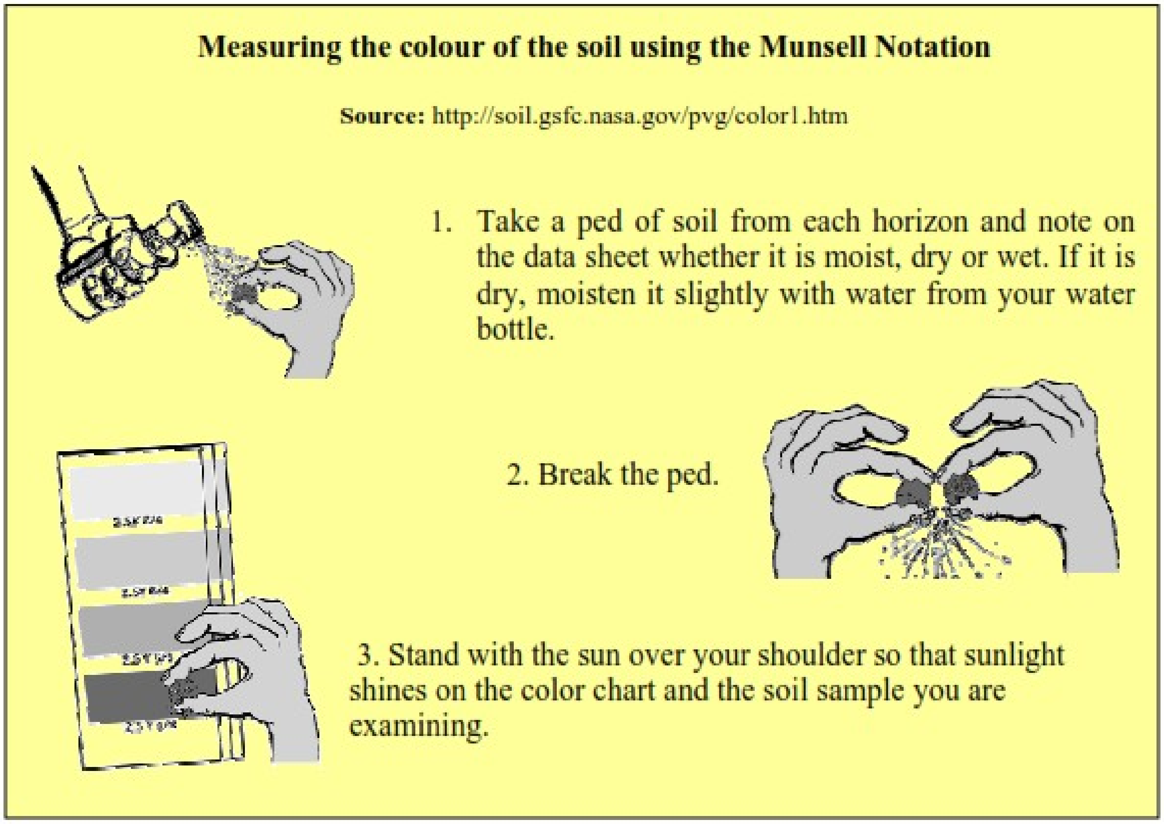


Figure 14: The Munsell system of color classification recognizes color in terms of three dimensions: *hue, value*, and *chroma* (Wikipedia, 2015b)



5.6 Soil Temperature

The temperature of the soil is an indicator of the energy needed to sustain the normal activity of plants and soil organisms. It is a physical property of soil that is of great concern. All plants and microorganisms in the soil exhibit different preferences for temperature, which constitutes the upper and lower limits of the tolerance range. Within this range, plants and microorganisms can live and carry out a complete life cycle of birth, growth, and reproduction. The optimum temperature is a narrow range between the upper and lower tolerance limits that is most favorable and where plants and microorganisms perform the best. Beyond the upper and lower limits of the optimum temperature range, growth and reproduction can slow down dramatically. The optimum temperature for different plants and organisms is widely variable.

The rate of physical, chemical, and biological processes is directly related to the changes in the soil temperature. Temperature can have a profound impact on the success of seed germination, root and shoot growth, nutrient uptake, and crop growth. In cold soils, the rate of biochemical reactions is slow. Decomposition and nutrient cycling can come to a complete stop as the activity of microorganisms decreases. For example, the activity of microbes that facilitate the oxidation of ammonium (NH_4^+) ions to nitrate ions (NO_3^-) occurs most readily at temperatures 27-32 ^oC and is severely slowed if the soil temperature is lowered to 10 ^oC. As a result, the availability of essential nutrients such as nitrogen, phosphorus, sulfur, and calcium is retarded, presenting adverse affects to higher plants. Temperature fluctuation can also provide benefits such as control of pests and diseases. In addition, the effect of freezing and thawing can have profound influences on the physical structure of the soil.

Figure 15: A soil temperature probe can be used to measure the temperature of the soil at various depths (http://www.ncusd203.org/madison/Links/teams/training.html)

Natural fluctuations in the soil temperature occur daily and annually as a result of seasonal and diurnal changes in the amount of incident solar radiation or sunlight. Temperature change is also caused by variation in air temperature, moisture content, soil color, slope of land, and vegetation cover. Dark soils can absorb more heat than lighter soils that reflect sunlight. As a result, dark soils warm or thaw faster in the spring than light soils. It should be noted, however, that the evaporation of moisture from the soil consumes heat, causing the soil to cool as the water evaporates at the surface of the soil. Since darker soils usually indicate higher moisture content, not all dark soils are warmer than light soils. Furthermore, soils that lie on south-facing slopes in the Northern Hemisphere receive more solar radiation throughout the year and are warmer in temperature. Vegetation also controls the amount of sunlight that can reach the ground surface. Bare soil cools and warms faster than vegetated soil that is insulated by vegetation.

Management practices can have significant effects on temperature of the soil. Management of soil temperature involves placing controls on drainage, structure, organic matter content, structure, and proper mulching techniques.

6.0 The Chemical Nature of Soils

The soil is the primary source of nutrients for vegetation and crops. If the soil lacks adequate quantities of nutrients, or if nutrients are locked up in an unavailable form due to the chemical properties of the soil, plants may become unhealthy and die. Soil chemistry is a branch of soil science that is concerned with chemical processes involving soil solids, soil solution, and soil air. Contemporary studies of the chemical nature of soil focus on chemical reactions in the soil that affect plant growth and ecological health, such as the relationship between acidity, fertilization, and crop yield. Since the 1960's studies in soil environmental chemistry and toxicology have emerged, which attempt to understand the fate, transport, and potential toxic impacts of contaminants that have been released into the soil and their impact on ecosystem and human health. Environmental soil chemistry concentrates on reactions between soil and heavy metals, pesticides, industrial contaminants, acid rain, and salts.

6.1 pH – Acidity and Alkalinity

pH is a measure of the concentration of hydrogen (H^+) ions in solution that is expressed as a negative logarithm (ie. pH = - log [H^+]). In other words, pH is a measure of the acidity or alkalinity of a material. The pH scale runs from 0-14, where a pH of 7 represents an equal concentration of acids and bases and is called neutral. Any pH reading below 7 is considered acidic and any pH above 7 is called alkaline. As the concentration of hydrogen ions increases (i.e. solution becomes more acidic) the pH decreases. High pH values indicate low acidity.

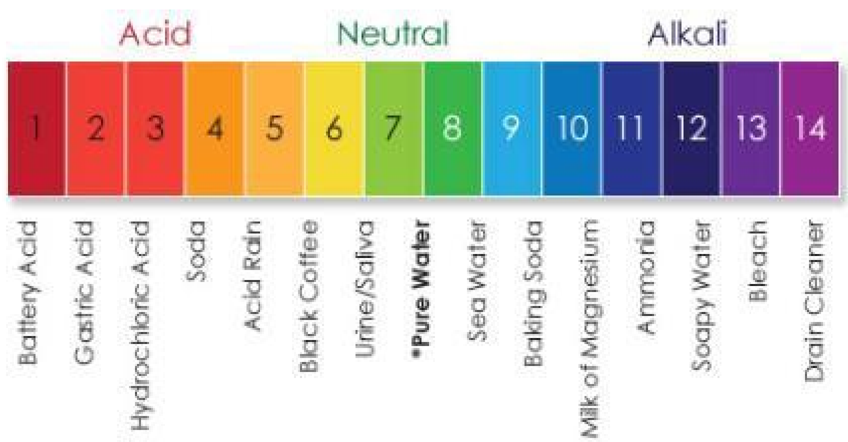


Figure 16: The pH Scale (Carmen's Science, n.d.)

Soil pH is one of the most informative properties of the soil and has a profound influence on plant growth. One of the most important influences exerted by pH is the solubility and plant-availability of essential nutrients. Nutrients that are held on the surface of organic matter and clay particles must first be dissolved into the soil solution before they can be absorbed by plants. In some cases, excessive dissolution of elements into the soil solution can be toxic to plants. In other cases, dissolution of highly mobile elements causes them to be carried away by water, leaving the soil devoid of that nutrient. For example, herbicides, pesticides, and fungicides are absorbed by the soil at certain pH values. Beyond certain pH values these compounds can become mobile and be removed by leaching, causing runoff and pollution of water systems elsewhere. Soil pH also has an influence on decomposition of agricultural and forestry residues, manure, sewage sludge, and other organic materials.

All plants and soil organisms exhibit different preferences for acidity in their environment. The ideal condition is the optimum pH range which can vary widely from one organism to another. Specific levels of acidity are needed to grow, thrive, and fight off disease. Some plants, such as potatoes, strawberries, and blueberries are acid-loving and have a preference for acidic soils. Others enjoy slightly alkaline soils. Examples include the plants of the brassica family (e.g. cabbage and cauliflower).

It is extremely rare to find plants that prefer soils at either extreme of the pH scale. The majority of plants often prefer a neutral or slightly acidic soil between the range of 6.0 and 7.5. Below 6.0, essential elements such as nitrogen, phosphorus, and potassium become less available, and as the pH approaches 5.5 elements such as aluminum, zinc, iron, and manganese become soluble and available for uptake by plants in excessive quantities that are then harmful to plant growth. In acidic soils, plants are more likely to take up toxic metals and experience heavy metal poisoning which can cause injury or death. At any pH above 7.5, essential nutrients are less available and symptoms of deficiency may result. The result can be seen as slow and stunted growth, yellowing of leaves, and thin growth of stems.

Soil **acidification** occurs often in areas with high levels of precipitation, where rainfall causes the leaching of appreciable quantities of basic cations. Acidification also occurs by addition of hydrogen through decomposition of organic matter, addition of acid-forming fertilizers, and exchange of basic cations for H^+ by the roots of plants. Soil alkalinity is caused by the addition of nitrogen fertilizers (e.g. nitrates, ammonium and urea), but could also be a reflection of basic parent materials such as limestone bedrock which is made up of calcium and magnesium carbonates. .

Any excessive acidity or alkalinity which may cause stress or fatality in plants and organisms can be corrected. Lowering of soil pH due to high alkalinity can be done by incorporating elemental sulfur into the soil and raising of pH can be done by soil application of liming materials such as ground limestone or industrial by-products that contain calcium oxides or hydroxides.

The Effect of PH on Plant Nutrient Availability

The thicker the bar, the more the available nutrient

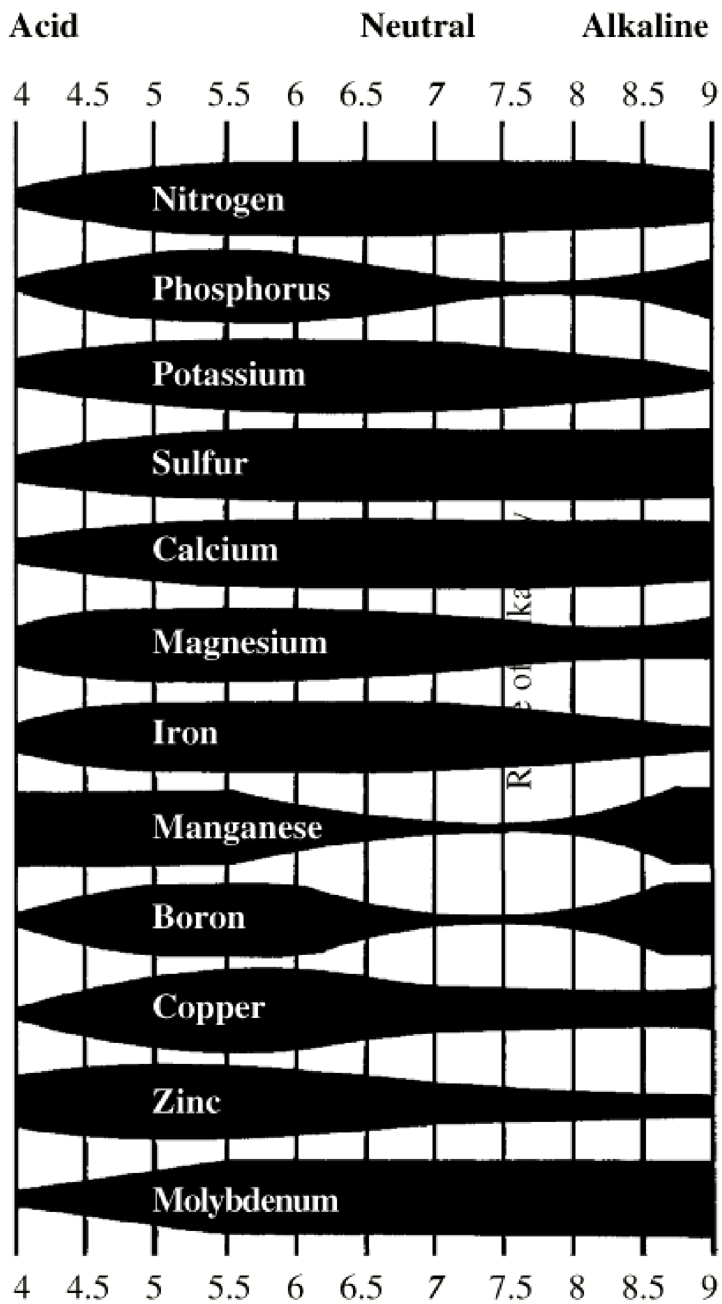


Figure 17: The change in availability of nutrients with changes in pH. **(**University of Arizona, 1998)

6.2 Cation Exchange Capacity

Cation exchange capacity (CEC) refers to the soil's ability to maintain reserves of positively charged ions know as cations. Cation exchange occurs when cations are exchanged between soil particles and the soil solution. The six most abundant exchangeable cations in the soil are calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}), sodium (Na^{2+}), aluminum (Al^{3+}) and hydrogen (H^{+}). CEC is influenced by the texture of the soil. CEC is higher in soils with higher clay and organic matter contents as these are the most chemically active fractions of the soil. In order to better understand this process, we must first investigate the properties of clay and organic matter that make them suitable for cation exchange.

The particles of fine clays and organic matter are called colloids. Two properties about colloids make them particularly suited for cation exchange. Colloids are extremely small in size, generally less than 1 µm (less than 0.001 mm) in diameter. The small size of colloidal particles means that they have extremely large surface area to volume ratios. In fact, the surface area of 1 g of colloidal clay is at least 1000 x that of sand. Second, **colloids** have negatively charged surfaces. Charges on the surface of clay colloids occur when an atom in the clay mineral r structure is substituted with an atom of similar radius but different charge. For example, Si^{4+} in a clay colloid can be replaced with Al^{3+} atoms. The balance is a negative charge. The negatively charged surfaces of the colloids serve to attract oppositely charged cations that are loosely held by electric forces. This loose attraction is referred to as adsorption.

Once adsorbed, mineral elements are stored on colloids preventing any losses from the soil. As a result, nutrient reserves are available to plant roots for uptake through exchange between colloids and soil solution. If cations are not held or adsorbed to colloids, such as in the case of a soil with low CEC, any added cations are susceptible to loss from the rooting zone of plants through leaching with percolating water. CEC is of particular importance in the application of pesticides and fertilizers. If the CEC of the soil is too low, the cations in these compounds are not adsorbed and will easily be leached away, possibly polluting underground or surface water resources elsewhere.

Not all cations are held with equal force by the soil colloids. As a general rule, atoms of increasing positive charge and smaller molecular radii are held with greater attraction. When cations are present in equal concentrations, the order of strength of attraction is summed as follows:

$$\mathbf{Al^{3+} > Ca^{2+} > Mg^{2+} > K^{+} = NH_4^{+} > Na^{+} > H^{+}}$$

In addition to the strength of adsorption, the relative concentration of cations in the soil solution also determines the degree of adsorption. The greater the concentration of an cation, the greater its adsorption.

Since not all cations are held equally tightly and differ in relative concentration, they are subject to exchange with other cations of greater attraction. Once cations are exchanged and released into the soil solution, they can be taken up by roots and soil organisms.

A low CEC value means that the soil is unable to hold nutrients that are applied through fertilization and therefore there will be limited availability of these nutrients to plants and microorganisms. Low CEC is generally a reflection of low levels of clay and organic colloids in the soil. In such a case, addition of organic matter should assist in raising the CEC of the soil. Soil pH is also important for CEC because as pH increases, the number of negative charges on the colloids increase, thereby increasing the CEC. The pH of a soil with low CEC can be increased by addition of lime.

Cation exchange capacity is an important property of the soil because it is a useful indicator of soil fertility, nutrient retention capacity, and the capacity to protect groundwater from contamination.

6.3 Essential Nutrients

One of the main reasons for the study of soil chemistry, soil pH, and cation exchange capacity is to understand how nutrients are processed and made available to the plants and organisms that need them. Plants require a combination of adequate air, water, light, and temperature to grow. In addition to these resources, plants also require a favorable concentration of 16 different elements or nutrients for growth and survival. These 16 nutrients are divided into two groups: *mineral* nutrients, and non-mineral nutrients. Non-mineral nutrients, namely hydrogen (H), oxygen (O), and carbon (C) are obtained from the air and water. In a process called photosynthesis, carbon dioxide from the air, and water from the soil are converted into starches and sugars. Non-mineral elements make up approximately 94% of plant tissues. The remaining 13 nutrients are mineral nutrients that are obtained in different quantities from the soil solution and absorbed through the plant's roots.

There are two main groups of mineral nutrients, each distinguished based on the quantity of the mineral that is required for healthy growth. Macronutrients are those nutrients that are required in relatively large quantities whereas micronutrients are required in comparatively small quantities.

The primary macronutrients are nitrogen (N), phosphorus (P), and potassium (K). Generally speaking, these are the first nutrients to be lacking from the soil, since they are used in the greatest quantity. The secondary macronutrients are calcium (Ca), magnesium (Mg), and sulphur (S). These are usually found in adequate quantities in the soil. The trace elements or micronutrients are boron (B), zinc (Zn), chlorine (Cl), manganese (Mn), molybdenum (Mo), and iron (Fe) and are generally obtained by recycling of organic matter. Nutrients are recycled within the soil environment to support plant needs. Plants grow normally until they run short of one or more nutrients. Growth and development become limited by the least available plant nutrient, regardless of how much of all the other nutrients are available to the plant. When one or more nutrients limit the plant's ability to perform normal tasks, we say that the plant is deficient in that particular nutrient. Deficiencies can cause discoloration or deformations of plant structures as well as declines in plant growth.

The 'barrel analogy' is used to demonstrate how deficiencies affect plants. In the barrel analogy, the level of water represents the level of production or yield from plants. The lowest plank of the barrel represents the limiting nutrient. In the example below the level of water is restricted solely by the limiting nutrient, nitrogen in this case, and falls to the same level as the nitrogen plank, unaffected by all others. When the level of the limiting nutrient is increased, the water is limited by the next most limiting nutrient.

There are two types of deficiencies. Real deficiencies are those that result from the lack of a nutrient's presence in the soil, whereas induced deficiencies are those that occur when high levels of one nutrient prevent the uptake of other nutrients. Real deficiencies occur when nutrients are removed from the system due to erosion, leaching, and harvesting of plants, without subsequent addition of nutrients to the soil. Soils that are deficient in one or more nutrients must be replenished to maintain long-term fertility and plant productivity. This can be done through the addition of nutrient fertilizers or through soil conservation practices that recycle ecosystem nutrients.

Mineral/Element	Chemical symbol	Main requirement/use by the plant
Macronutrients		
Nitrogen	N	Plant growth; proteins; enzymes; hormones; photosynthesis
Sulfur	S	Amino acids and proteins; chlorophyll; disease resistance; seed production
Phosphorus	P	Energy compounds; root development; ripening; flowering
Potassium	K	Fruit quality; water balance; disease resistance
Calcium	Ca	Cell walls; root and leaf development; fruit ripening and quality
Magnesium	Mg	Chlorophyll (green color); seed germination

Table 3: Role of soil macronutrients in plant lifecycle (University of Arizona, 2007)

Mineral/Element	Chemical symbol	Main requirement/use by the plant
Micronutrients		
Copper	Cu	Chlorophyll; protein formation
Zinc	Zn	Hormones/enzymes; plant height
Manganese	Mn	Photosynthesis; enzymes
Iron	Fe	Photosynthesis
Boron	B	Development/growth of new shoots and roots; flowering, fruit set and development
Molybdenum	Mo	Nitrogen metabolism
Chloride	Cl	Photosynthesis; gas exchange; water balance

Table 4: Role of soil micronutrients in plant lifecycle (University of Arizona, 2007)

7.0 The Biological Nature of Soils

Healthy soils consist of a complementary blend of minerals, rocks, water, air, and organic matter. However, the soil is so much more, containing in its body a concealed world of live and complex ecosystems, which include a variety of bacteria, fungi, protozoa and other living organisms. **Soil biota** are organisms that spend all or a portion of their lifecycle within the soil or on its immediate surface.

Soil communities are very diverse in size and number of species, which are defined by the chemical and physical nature of the soil body. The physical and chemical nature of the soil in addition to factors such as vegetation, climate, and nutrient content shape the appropriate niches for a myriad of flora and fauna that call the soil home. In one gram of any given body of soil, millions of individual soil organisms can be found carrying out their biological functions and executing the vital processes that make life on earth possible. In fact, soil is one of the most diverse and complex ecosystems on earth, providing shelter to thousands of different species of organisms.

The incredible diversity of life forms that inhabit the soil, range in size from single-cellular submicroscopic organisms such as viruses to earthworms to larger, more complex organisms such as gophers and ground squirrels. Soil flora and fauna are categorized in terms of size as **macrobiota***,* **mesobiota**, and **microbiota**. Macrobiota refers to the series of organisms that are visible to the naked eye that dig the soil for shelter and feed on or in the soil. Macrobiota include vertebrates such as mice, moles, and groundhogs and invertebrates such as ants, termites, earthworms and snails. Mesobiota are 0.1-2 mm in diameter and generally live within the soil pores. These organisms such as springtails have little ability to burrow and generally feed on organic material and other soil organisms to survive. Microbiota which are comprised mostly of bacteria, fungi, algae and protozoa are the smallest organisms. They are extremely abundant and diverse and are able to decompose almost all existing residual organic matter.

The presence and functions of soil organisms are so vital that soil biodiversity is often used as an indication of the soil's quality and health. This is, of course, attributed to the fact that the routine activities of soil organisms moderate water flow, decompose and recycle organic matter, and make it possible to have clean water, clean air, and healthy, productive plants.

7.1 Soil Biodiversity

Soil biodiversity is defined as the variety of life found in soil, including numerous species of invertebrates and microorganisms, soil flora, plant roots, mammals, birds, reptiles and amphibians. Soil communities are among the most species-rich areas in terrestrial ecosystems. Most of the organisms inhabiting soil ecosystems are found within the top 10 cm of the soil profile. However, there are many factors that influence the diversity of organisms within soil ecosystems.

There are several factors that can contribute to the biodiversity within soil. These factors include soil texture, soil structure, abiotic conditions (sunlight, rainfall, wind) and interactions with other organisms. The amount of organic matter found in soil has a large impact on the surrounding biodiversity as it impacts soil fertility, soil structure, workability and water-holding capacity. These factors influence the number and species of plants that are capable of growing in the soil, impacting the wildlife in the surrounding area. Soil structure is important because it affects the stability of soil and its resistance to degradation under pressure. Structure is strongly influenced by texture, organic matter, compaction and biological activities. Much like soil texture, soil structure can also impact the organisms living within the soil. Good structure generally means the presence of large pores between particles. Soils with good structure increase water-holding capacity, promote root growth, maintain aeration and drainage provide a better habitat for organisms and reduce erosion risk. All of these factors contribute to the biodiversity within and on top of soil.

As the knowledge of soil biology increases, the threats to soil biodiversity also become evident. Indirect effects on biodiversity include structural decay, erosion and organic matter decline. These factors influence habitat for organisms within the soil and contribute to biodiversity decline. Direct impacts on biodiversity include contamination of soils through salinization and pollutants. The impact of global change on biodiversity within soil ecosystems is not yet known, however, communities with high resiliency will not be impacted as greatly as communities with low resiliency. Climate change will have impacts on local communities as there is a strong connection between soil formation, soil structure and climate.

Soil ecosystems with higher levels of biodiversity result in more productive, sustainable communities. These communities are also more resistant to changes in surrounding biotic and abiotic conditions. Increased biodiversity leads to increased redundancy in an ecosystem. High redundancy allows one species to substitute for another, such that functions are continuously achieved, even with the loss of one species. With increased redundancy, soil ecosystems also have higher resistance to perturbations. More diverse systems are also more resilient following perturbations. Resilient ecosystems can withstand shocks and rebuild themselves when necessary. This is beneficial in changing environments.

The vast diversity of species found in soil communities impact soil quality and functioning by providing essential services to the abiotic components of the soil. Due to the extensive functions of soil biota, declining soil biodiversity and its consequences on soil food web interaction processes will have dramatic negative impacts on ecosystem processes, ecosystem stability, community composition and community stability.

Function	Comments
Degradation of organic matter	The most obvious function carried out by soil biota. Up to 80% of the organic material fixed by primary producers flows to the detrital food chain.
Cycling of nutrients	As organic matter is processed, nutrients are released into the environment and become available for recycling back to primary producers.
Sequestration of carbon	Organic residues from decomposition become part of the stable structural carbon pools of terrestrial ecosystems.
Production and consumption of trace gases	As soil biota degrade organic material, recycle its nutrients, and sequester its carbon, they also carry out other functions that are important. Soil microbial activity leads to the production and consumption of a variety of trace gases (carbon dioxide, nitrous oxide, methane, carbon monoxide and sulfur gases), many of which are important greenhouse gases.
Degradation of water, air and soil pollutants	Soil and sediment biota processes (degrade, produce, alter) a variety of water, soil and air pollutants of anthropogenic origin, including pesticides and industrial compounds.
Development and maintenance of physical structure	Soil biota help to produce and maintain the physical structure of terrestrial ecosystems. Organisms are critical agents in soil formation. This role is expressed directly via the burrowing and tunneling activities of fauna and their production of sticky compounds, and indirectly via the production of structural organic matter.

Table 5: Soil biota functions that can be used to evaluate the links between diversity and ecosystem function.

7.2 Organisms of the Soil

The soil is a complex ecosystem with a community of diverse organisms that occupy a broad range of niches. Like other ecosystems of the earth, the soil flora and fauna are intimately related and interact through a complex network of energy and nutrient transfers known as the food web. The soil food web is the community of organisms that spend all or a portion of their lives in or around the soil.

The energy to fuel the food web is obtained from the sun by **primary producers** in fixing carbon dioxide from the atmosphere into sugars. Primary producers include plants, lichens, moss, photosynthetic bacteria, and algae.

Primary consumers of the soil live off of photosynthesizing organisms or their by-products. **Detritivores** are those organisms that consume dead and decaying plants, while **herbivores** consume living plants. The primary consumers are themselves sources of nutrition for higher tropic levels, such as **secondary consumers**, which are in turn food for **tertiary consumers**. When these organisms die and decompose, nutrients are once again returned to the soil and made available to plants and other soil organisms.

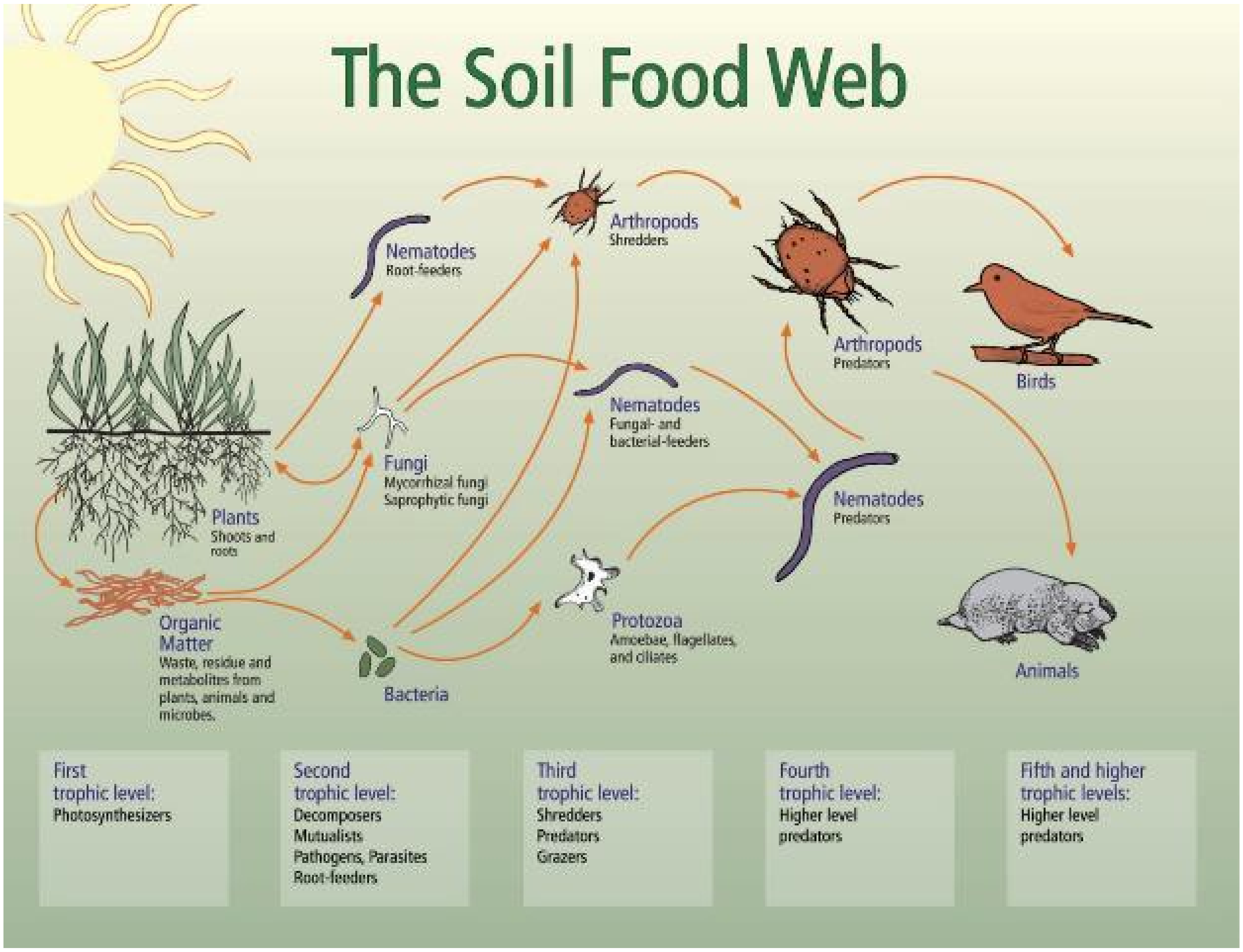


Figure 18: The food web of the soil (USDA, n.d.)

7.2.1 Soil Microbiota

Microorganisms are the smallest form of life that often exist in single-celled colonies. They are generally not visible to the naked eye. Microorganisms are most concentrated in the top-most horizons of the soil that are enriched in organic food sources; around roots, on humus, and in dead and decaying litter. These organisms are the key decomposers of organic matter, however they carry out additional functions such as nitrogen fixation, aggregate formation, and production of antibiotics.

Algae

Algae are photosynthetic organisms that capture the energy of the sun to convert inorganic substances into organic matter. Algae need light to carry out their photosynthetic process, and therefore are found near the surface of the soil. Some algae are also able to capture nitrogen from the air as in nitrogen fixation, and provide nearby plants with this nutrient. Algae provide the important advantage of improved soil structure. They produce slimy (gelatinous) substances that glue soil particles into aggregates, helping to improve the strength and stability of the soil.

Fungi

Fungi come in many different species, sizes, and shapes in the soil, including threadlike colonies, single-celled yeasts, slime molds, and mushrooms. The most important soil fungi are molds, mushrooms, and mycorrhizae. Unlike algae, fungi are not photosynthetic, and must therefore obtain their energy from breaking down the organic matter of the soil. Fungi are the first organisms to attack fresh, organic residues before any other organisms join in the decomposition process. They tend to break down the more complex compounds and in the process, help release nutrients from organic matter into the soil. Fungi are also able to produce plant hormones and antibiotics that encourage growth and destroy diseases and pests. In addition, the network of fungal hyphae helps strengthen soil structure and stabilize aggregates by secreting a sticky gel that glues mineral and organic matter.

Mycorrhizae are a special group of fungi that live on or in plant roots and form symbiotic (mutually beneficial) relationships with the plants. Mycorrhizae infect the roots of plants and send out root-like structures called hyphae. The hyphae of fungi extend into the soil, and increase the contact of roots with soil. Hyphae absorb water and nutrient and provide them to the plant roots. Mycorrhizae also protect the plant roots against pest nematodes that cannot penetrate through the thick fungal network. In return, the fungi received nutrients and carbohydrates from the root of the plants they live on.

Figure 19: Root heavily infected with micorrhizal fungi (Phys Org, n.d.)

Bacteria

Bacteria are the most numerous of the soil organisms with capacity of rapid reproduction. In fact, every teaspoon of soil can carry billions of individual bacteria. Their wide range of tolerance allows them to exist in a wide range of habitats, including the guts of living organisms, oceans, freshwater, compost piles, and soils.

Bacteria are one-celled organisms that are either autotrophic or heterotrophic. Autotrophic bacteria obtain their energy from the oxidation of inorganic substances such as ammonium, sulphur, and carbon dioxide. In the process, they increase the solubility of these nutrients for plants to absorb. Heterotrophic bacteria cannot make their own energy, and generally obtain it from the breakdown of organic matter in the soil. Unlike fungi, bacteria attack the more simple organic compounds. During this decomposition, bacteria help to release important elements for higher plants. Bacteria also make and release natural plant growth hormones to stimulate root growth. Some bacteria are also able to fix nitrogen from the air such as in the process of biological nitrogen fixation, both in association with and independently of legumes.

Actinomycetes

Actinomycetes are a type of bacteria that have fungi like characteristics including their thread-like structure. Actinomycetes break down lignin, a large and complex molecule found in the tissues of plant stems that is difficult for other organisms to break down. In addition, they produce antibiotics to fight diseases of roots. Actinomycetes develop in moist, well aerated soil, and are responsible for the rich organic scent of soil immediately following ploughing.

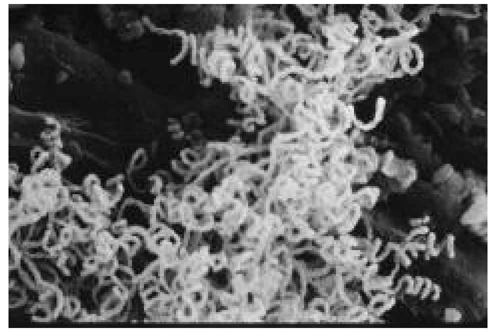


Figure 20: Actinomycetes, thread-like organisms. **(**USDA, n.d.)

Protozoa

Protozoa are single-celled organisms that are considered to be the most diverse and numerous of the soil microfauna. They thrive in moist, well-drained soils where they can crawl or swim in the water around soil particles and predate on organic materials, bacteria, fungi, and other protozoa. They are considered to be secondary consumers of the soil, however they do not contribute significantly to decay and nutrient release in the soil.

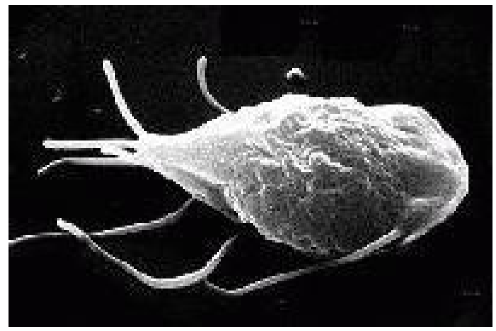


Figure 21: Protozoa (USDA, n.d.)

Nematodes

Nematodes, also called threadworms or eelworms are generally microscopic in scale. They are found in abundance in almost all soils. Nematodes can be either beneficial or detrimental to the soil environment based on the particular species. Predatory nematodes consume plant litter, bacteria, fungi, algae, protozoa, and garden pests. Pest nematodes however, can attack the roots of practically all plant species, causing serious damage, especially to vegetable crops.

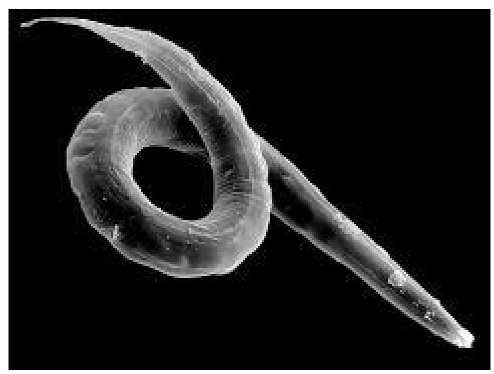


Figure 22: Nematode (USDA, n.d.)

7.2.2 Soil Mesobiota

Earthworms

Earthworms are a type of soil fauna with enormous favorable influences on soil and crop productivity. Earthworms burrow through the upper 15-35 cm of the soil and ingest dead organic matter, minerals, and bacteria. This material is passed through the digestive system of the worms where it is mixed and is expelled as fecal casts. Casts are extremely rich in nutrient and organic content and contribute to the fertility as well as aggregation of the soil. A good population of earthworms can process 20,000 pounds of topsoil per year!

Furthermore, the burrowing action of earthworms creates tunnels (biopores) that enhance aeration, allowing air to enter deeper into the soil and stimulate nutrient cycling and oxidative reactions. Burrowing also opens ways for water to infiltrate through the soil, thereby reducing runoff and in turn enhancing groundwater recharge.

Comparisons between soils with and without earthworms have revealed reoccurring patterns of improved soil characteristics and productivity. These include lower bulk density, increased structural stability, and

Figure 23: Earthworm (Britannica Kids, n.d)

increased cation exchange capacity, in addition to higher concentrations of calcium, potassium, phosphorus, and nitrogen.

Most earthworms prefer near-neutral soil pH and moist habitats with high organic matter content. In drier areas, earthworms tend to dry up and without organic matter there is no source of food for earthworms. This is why earthworms thrive best in low to no-tillage environments. Tillage tends to dry the soil, bury organic plant residue deeper in the soil profile, and render the soil more prone to freezing in cold winters. Tillage also destroys the burrows and kills the earthworms themselves.

As a rule, earthworm numbers can be increased by reducing or eliminating tillage, reducing organic matter particle size, addition of animal manures, and minimizing pesticide use.

Termites

Termites are a significant force behind organic matter decomposition in or at the surface of the soil. In some tropical climates they build mud nests or honeycombed mounds that can be as tall as 6m high. Over 1 million termites can reside in each mound, where they lead very complex social lives.

Termites contribute heavily to the mixing of soil and organic material as they transport extensive amounts of soil from lower layers to the surface of the soil.

Figure 24: Termite.(bioold, 1999)

However, unlike earthworms, termites render the soil more compact as they cement together the soil particles for their mounds. In addition, termites differ from earthworms in that their deposits have much lower organic matter content than the surrounding soil. Crop production in soils where termite mounds existed is poor for these reasons. On the contrary, termites do offer the benefit of accelerated decay of dead trees and grasses.

Ants

The impact of ants on the soil environment is much more negligible than that of earthworms and termites and is only locally notable. Ants build nests and mounds that differ substantially from conspicuous mounds to hidden underground nests. However, ants do bring about an extensive turnover in the soil when deeper subsoil is brought to the surface of the earth. In addition, some ants are quite efficient at breaking down of woody debris.

Arthropods

Arthropods are a group of soil organisms with exoskeletons and jointed limbs that are still visible to the naked eye. Among them are sowbugs, millipedes, slugs, snails, and springtails. These organisms are the primary decomposers in the soil, eating and shredding large organic particles and mixing residue with the soil. The waste produced by arthropods is extremely rich in plant nutrients that are released after it is further worked on by bacteria and fungi.

7.2.3 Soil Macrobiota

Macrofauna

Large animals, including moles, rabbits, snakes, prairie dogs, and badgers are all considered to be a part of the soil community of organisms. They burrow the soil and spend a part of their lives below the soil, creating tunnels that decrease erosion. Some consume smaller soil organisms such as worms while others consume vegetation. Many soil macrofauna are considered to be a nuisance to agriculture since their underground tunnelling can be problematic to heavy farming machinery.

Macroflora

Roots of plants, trees, and shrubs make up the macroflora of the soil. If soil physical and chemical conditions are unsuitable, plant roots do not grow properly and crops can fail. Plant roots impact the soil by influencing the formation of aggregates, as well as by releasing root exudates that nourish soil organisms.

7.3 Benefits of Soil Organisms

7.3.1 Organic Matter Decomposition and Nutrient Cycling

The matter that makes up the body of all humans, animals, and plants was once a part of the body of soil that was over time transformed from plant matter to animal flesh and eventually returned back to the soil. This important cycle of life would not continue if it were not for the contribution of soil flora and fauna to organic matter decomposition. During decomposition, complex organic chemicals are broken down into physically smaller and chemically simpler compounds. In the process, carbon is either released to the atmosphere as CO_2, or it is **sequestered** within the body of soil organisms or stored in organic humus compounds.

Humus, the organic portion of topsoil, consists of dead plant and animal residue that has been acted upon and decayed by soil biota. The process of decay occurs because soil organisms use organic carbon compounds from organic matter for energy and to make cell matter. Once decayed, nutrients that were trapped in the original organic matter – carbon, nitrogen, sulphur, and phosphorus – are returned to the soil to replenish its fertility. This is the basis of nutrient cycling in all ecosystems of the world.

7.3.2 Soil Structure and Stability

When soil biota break down dead roots and decompose organic matter, they convert complex carbon compounds into simpler polysaccharides. Long and flexible polysaccharides act like glue-like matter to hold soil particles together as aggregates. This binding of individual soil particles with adjacent particles is a significant feature that helps improve the stability of the soil. Aggregation also prevents or minimizes runoff and erosion, permits improved aeration and easy water drainage, as well as better movement of plant nutrients.

7.3.3 Inorganic Transformations

The nitrogen, sulphur, and phosphorus contained in organic matter exist in an organic form, and are unavailable to higher plants. For the most part plants are only able to take up nutrients in their inorganic mineral forms. The organically-bound forms of the nutrients must be converted into plant-available forms first by microbial action. This process is called mineralization. Mineralization of organic material liberates carbon dioxide, ammonium (which is rapidly converted to nitrates), sulphate, and phosphate in addition to inorganic forms of other elements.

While doing this, some soil organisms take up nutrients to be used for their own means and sequester them within their body. The nutrients taken up by the soilorganisms are immobilized and therefore unavailable to plants. It is not until these organisms die and decay that other soil organisms can make the nutrients tied up in their bodies available to higher plants.

In addition, soil biota can control the form of nutrients available in the soil. For example, the bacteria *Nitrosomonas* and *Nitrobacter* facilitate the oxidation of nitrogen in the form of ammonium (NH_4^+) to nitrite (NO_2^-) and nitrate (NO_3^-), respectively. In another case, the bacteria *Thiobacillus* facilitate the oxidation of elemental sulphur to sulphuric acid. The bacteria that facilitate oxidation of nitrogen, sulphur, and other compounds, use the energy released during oxidation to drive their own metabolisms.

7.3.4 Nitrogen Fixation

Biological Nitrogen Fixation is the process through which biological agents convert nitrogen from the air (N_2) into a form of nitrogen that is available to plants. This process is carried out in the most part by soil bacteria that exist in a mutually beneficial relationship with plants. The most commonly recognized form of this relationship is that between rhizobium and legume root-nodules. These bacteria thrive on the surface of roots of specific legumes and benefit from the supply of proteins and sugars that released through exudates. In turn, the bacteria 'fix' large quantities of elemental atmospheric nitrogen into plant-available forms of nitrogen. Both plants and soil organisms benefit from this mutually beneficial symbiotic relationship.

Many legumes are able to supply their own nitrogen through fixation. Nearly two thirds of the world's nitrogen supply is obtained from biological nitrogen fixation. The practice of green manuring is used all around the world to increase the nitrogen content of the soil by planting legumes. In this practice, legumes are planted solely to improve the fertility of the soil without the use of synthetic agricultural fertilizers.

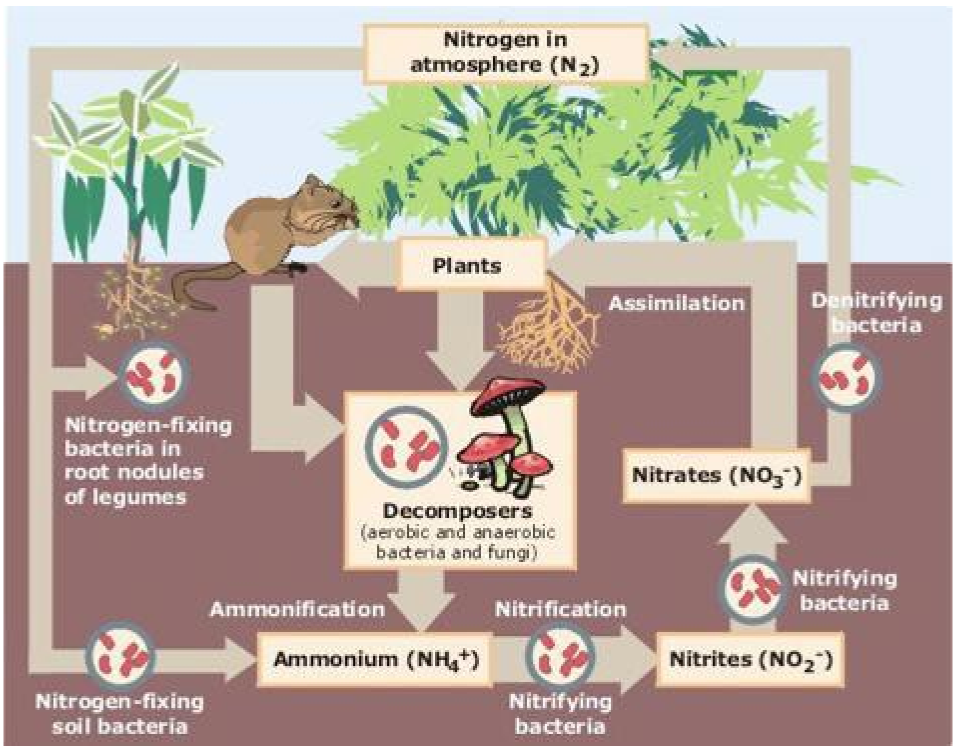


Figure 25: The nitrogen cycle (Wikipedia, 2013)

7.3.5 Degradation of Pollutants

Many soil microorganisms have the remarkable ability to break down or degrade or immobilize hazardous substances, including organic compounds, into less toxic or non-toxic substances. Examples of these materials include pesticides, herbicides, petroleum products, and heavy metals. An important implication of pollutant degradation is purification of water and prevention of water pollution.

Soil science professionals have taken advantage of the soil's ability to breakdown harmful substances to develop methods for remediation of contaminated soils using the soil's own organisms. This process is called **bioremediation**. Bioremediation is a method of cleaning contaminated soil using microorganisms such as bacteria to break down spilled pollutants within the soil. There are two ways of bioremediating a contaminated site.

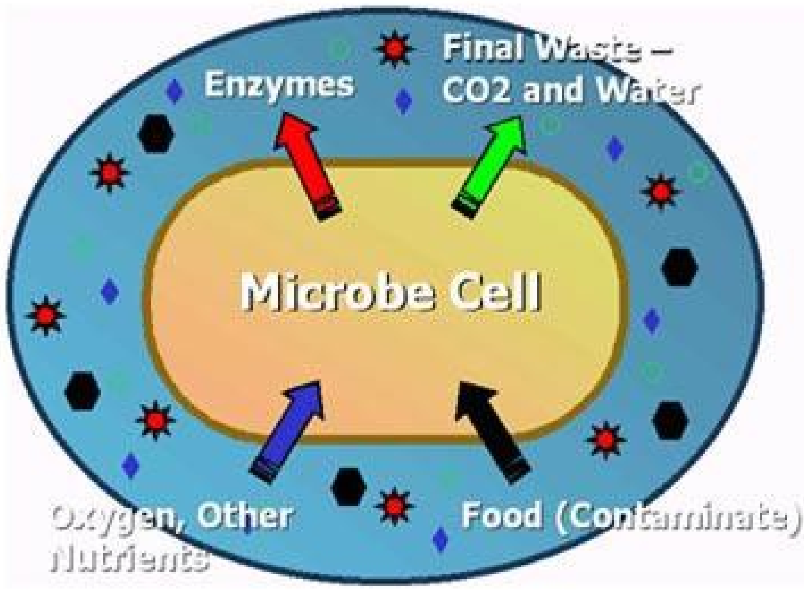


Figure 26: Bioremediation. Oxygen and nutrients are added to the soil to encourage multiplication of existing microbe cells (alternatively, new microbe populations are added to the soil). Soil microbes release enzymes that help them to consume contaminants as food. Harmless biological wastes such as carbon dioxide and water are released (Integra Environmental, n.d.)

One method, **biostimulation** modifies the environment of the soil so as to render it more favorable to the growth and development of soil organisms. Increased aeration and addition of fertilizing nutrients such as phosphorus, nitrogen, and potassium allow the rapid and persistent reproduction of already present microorganisms. The immense population of microbes, bacteria, and fungi in the soil naturally degrade and destroy any chemical pollutants in the soil. In contrast, **bioaugmentation** involves the introduction of non-indigenous microbial populations to speed up the degradation process.

8.0 Soil Degradation

It is without a doubt that humans and soils have evolved mutually throughout history; human survival has been linked to the health of the soil, and the health of the soil has been linked to the humans that use it. When inappropriate human use, or perhaps abuse, of the land renders it less vigorous and less healthy, we say that the land has been **degraded**. Soil degradation occurs as a result of both natural and human-induced processes that reduce its potential productivity. Changes in the physical, chemical, and biological nature of the soil that are brought about by inappropriate land-use practices and bad management reduce the soil's ability to support plant and animal growth. The soil may decline in available moisture, nutrients, and biological activity.

During the past 50 years, inappropriate land use has degraded about 5 billion ha of the Earth's vegetated land. The figure amounts to approximately 23% of the world's previously usable land and is expanding at a rate of 9 million ha per year .

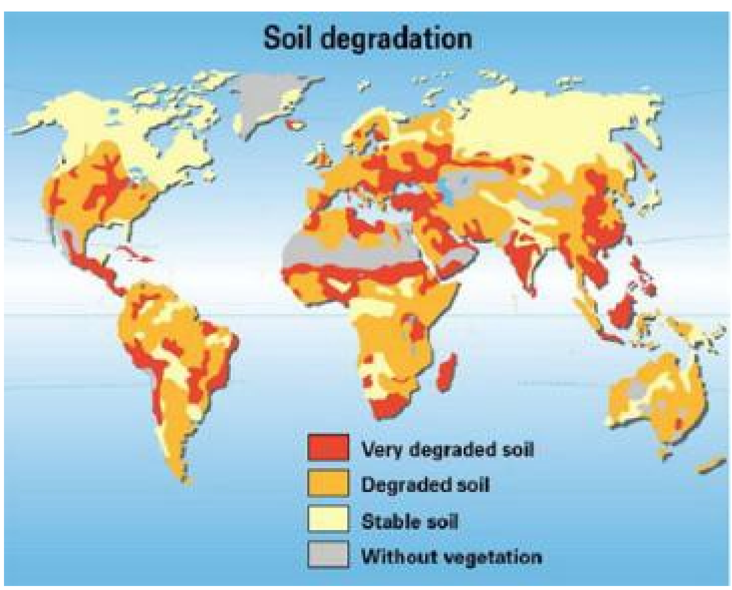


Figure 27: The state of soil degradation in the world in 1997 (Greenfieldgeography, n.d.)

Soil degradation is a result of economic, social, and political pressures on the land. It occurs primarily due to overgrazing (35%), deforestation (30%), agricultural activities (27%), overexploitation of vegetation (7%) and industrial activities (1%). The results of these activities are generally manifested on the soil as loss of organic matter, salinization, desertification, acidification, compaction, contamination and erosion. While continued soil degradation will lead to loss of arable land and declines in food production, a 2015 report on the status of the world's soil resources by the United Nations states that degradation can be curtailed and reversed. Sustainable soil management practices and policies that require implementation of these practices are key to improving soil conditions.

8.1 Organic Matter Depletion

The total organic matter content retained by the soil system is a function of the organic matter gains and losses. The quantity of organic matter entering the soil is determined by primary production of plants and litter and fine root inputs, and the amount leaving is controlled by erosion and microorganism decay of organic matter. The organic matter content of the soil depends on texture, drainage, vegetation, and erosion. In general, coarse textured soils (sands) have less organic matter than finer textured soils (clays); well drained soils less than poorly drained ones; soils developed under trees less than those developed under grasses; and eroded soils less than those which have not been subject to past erosion.

The role of organic matter in soil is exceptionally important, as it influences all physical, chemical, and biological properties of the soil. Without organic matter as a cementing agent, soil particles would not be able to bind together to form aggregates that strengthen and stabilize the structure of the soil. The soil would become weak and easily prone to erosion. Soil porosity and water-retention would also be reduced, meaning that any incident precipitation would be inhibited from entering the surface of the soil and result in runoff. Soil organic matter also contains a huge portion of the soil's essential nutrient reserves and accounts for more than half of the soil's cation exchange capacity. Nutrients such as phosphorous, nitrogen, sulphur, and micronutrients are safely stored on the surface of organic colloids to be taken up by plants when needed. Organic matter is also one of the main resources that supply organisms with the energy needed for growth and reproduction.The removal or depletion of organic matter can have harmful impacts on the soil system. Depletion occurs when the quantity of organic matter entering the soil is decreased and the amount of organic matter leaving the soil is increased. For example, the removal or burning of crop residue prevents fresh organic material from entering the soil. Tillage increases the rate of organic matter breakdown by soil organisms. Physical removal of topsoil by wind and water erosion dramatically reduces the organic matter content since the topsoil is the part of the soil profile with the highest organic matter concentration.

8.2 Salinization

Salinization occurs when water soluble salts – sodium, potassium, calcium, magnesium, and chlorine – accumulate in excess concentrations in the root zone of plants to such an extent that they lead to degradation of soil and vegetation. When salinization of the soil is due mainly to the concentration of excess sodium, it is referred to as **sodicity**.

Soil salinization may occur naturally or due to conditions resulting from anthropogenic mismanagement of the land. Salinization occurs when conditions of low rainfall, high evaporation, high water table, and the presence of soluble salts in the soil co-occur and work hand in hand to augment salt build-up.

In poorly drained soils, where the groundwater table is 9 feet or less from the surface of the soil, water is unable to leach down, and instead rises to the surface by **capillary action**. Capillary action is the natural upward movement of water between soil particles. In hot and dry regions, this water leaves the surface of the soil through evaporation. Since groundwater contains naturally dissolved salts, the water evaporates leaving salts behind. The phenomenon repeats constantly, and over time salts concentrate until they reach levels in the root zone that are detrimental to plants.

8.3 Desertification, Causes and Implications

Desertification is arguably the world's most threatening form of soil degradation and affects over one billion people worldwide, many of them among the poorest in the world. Desertification is not necessarily the expansion of existing deserts; rather it is the degradation and deterioration of fertile arable land, caused chiefly by deforestation, overgrazing, overcultivation, and poor irrigation.

Desertification occurs on all continents of the world except Antarctica, but chiefly impacts the world's drylands. These include arid, semi-arid, and dry sub-humid regions where potential evapotranspiration often exceeds precipitation, and vegetation cover is already sparse. With excessive pressures of agriculture, deforestation, and overgrazing, the natural vegetation cover can be reduced or completely eliminated, resulting in desert- like conditions. Desertification severely decreases the productive capacity of the land, which leads to a decline in agricultural productivity, food and water scarcity, malnutrition, poverty, and ultimately mass migration out of degraded regions.

8.3.1 Natural Factors that reinforce Desertification

The soils of arid lands are naturally characterized by shallow depths, insignificant organic matter content, negligible leaching capacity, absence of structure, high salinity, and low fertility. In arid regions, a low precipitation regime means that the land can only support and carry sparse vegetation cover. As a result, only a thin organic layer accumulates by the slow decomposition of plant remains. Soluble salts and sediments leach to shallow depths or remain at the surface due to the low precipitation regime. Violent dust storms and aggressive thunderstorms cause intensive land erosion and carry away much of the topsoil containing the nutrients and organic matter, leaving the soil even more infertile and unproductive.

8.3.2 Overgrazing

Overgrazing is the single largest and most devastating cause of desertification in arid lands. Livestock are the main source of income and a way of life in many developing countries. Domestic stocks are widely diverse and consist of camels, donkeys, horses, cows, sheep and goats.

In many arid regions, the forage and overgrazing of livestock causes a chain of degradation, critically reducing vegetation cover and soil fertility, as well as increasing erosion and chance of flooding. Domestic animals rapidly clear vegetation, placing stress on a land that already has a low vegetation cover. They also move in large groups and have sharp hooves that easily break up the soil, leaving it susceptible to erosion. Erosion decreases fertile organic matter content of the soil. The lack of organic matter can lead to desertification through reduced nutrient availability for plant growth.

Grazing and trampling causes soil compaction and degradation of the soil structure. The result is decreased soil permeability and plugging of pores which reduces the ability of water to penetrate the soil by infiltration and percolation. Runoff occurs when rainfall intensity exceeds the infiltration capacity of the top-soil. Soil moisture is decreased due to decreased soil organic matter and erosion is intensified because of livestock action. Water erosion may also carry sediments to streams, causing flooding and accumulation of salts.

8.3.3 Intense and Improper Agricultural Practices

When land is cleared and tilled, much of the natural vegetation is removed in anticipation for agriculture. The soil is suddenly bare and exposed to erosive forces such as intense wind and thunderstorms that occur frequently in arid regions. Substantial quantities of fertile topsoil and organic matter are removed. The outcome is a considerable decrease in fertility, water-holding capacity, and loss of structural aggregation. With minimal moisture and nutrient content, the soil loses any ability to support vegetative growth. This ultimately leads to the creation of deserts.

8.3.4 Mismanagement of Irrigation

Proper irrigation is one of the biggest challenges in arid lands where a moisture deficiency makes it impossible for farming to occur without artificial irrigation. However, irrigation in arid lands can further enhance desertification through salinization and alkalinization.

Salinization occurs when irrigation water evaporates quickly, leaving natural salts (e.g. chlorides, sulphates, and carbonates) at the surface of the soil. Over a long time, excessive quantities of salts accumulate at or near the soil surface making it increasing difficult for plants to extract water from the soil.

Alkalinization is a similar process, where the accumulation of sodium ions causes the disintegration of soil aggregates, resulting in a weakened soil structure. Poor soil structure generally leads to decreased porosity and aeration, reduced infiltration, oxygen deficiency, and increased runoff and erosion.

8.4 Acidification

Acidification is a major land degradation issue. It is a natural process that can be aggravated by poor agricultural and forestry practices. Soil acidification is a decrease in the pH of the soil beyond those ranges tolerable by plants and soil organisms. When the pH of soil declines to levels far from ideal, plants may experience deficiencies in essential nutrients such as molybdenum, boron, calcium, magnesium and potassium, while toxic elements such as aluminium, manganese, and iron become abundant in higher concentrations.

By far the most common causes of soil acidification are attributed to high rainfall and excessive use of ammonium-based fertilizers. While acid rain is one contributor to soil acidification, high quantities of rainfall also naturally cause the leaching of soluble basic cations such as calcium and magnesium and their replacement by acid cations such as aluminium and hydrogen. Nitrogen-based fertilizers also cause a decalcifying and acidifying effect on the soil. When agricultural crops or forests are harvested and removed from the land, basic elements are permanently removed. This is the means by which these practices exacerbate the rate of soil acidification.

When acidification occurs, uptake of heavy metals increase and may cause toxicity in plants, whereas the concentration and availability of necessary nutrients decreases. The result is reduced crop yield and vegetation cover, leading to accelerated runoff and erosion. Soil microorganisms would also be negatively impacted by toxities, preventing the continued recycling of nutrients.

8.5 Compaction

Soil compaction is the increase in bulk density of the soil that occurs when soil particles are packed closer together, reducing the pore space between them. Compaction is a serious problem because it reduces the productive capacity of the land.

Soil compaction is induced in two ways. When heavy agricultural machinery is used to till the soil and harvest crops, the soil becomes compressed under the pressure of the machine's heavy weight. This is called mechanical compaction. Compaction also occurs when grazing animals roam the land in large herds, their hooves pushing the soil particles tighter together.

Soil compaction is more likely to occur when soils are wet and has several implications. When the porosity of the soil is reduced, infiltration rates decline, causing accelerated runoff and erosion. Also, when soils are compacted, root growth becomes restricted, causing a reduction in water and nutrient uptake, and eventually reducing growth and yield. This is bad news for farmers, who depend heavily on the economic capacity of the land. The population and diversity of micro and macroorganisms is also adversely affected by the lack of air and water circulation. Decreased soil microorganism activity leads to decreased organic matter decomposition, and diminishes the availability of nutrients.

8.6 Contamination

Soil pollution is associated with serious and catastrophic environmental impacts. Soil contamination results when hazardous chemicals are spilled or buried directly into the soil, or when they migrate from elsewhere with air and water and deposit in the soil. Common soil contaminants include pesticides and PCBs, oil, road salt, and elements such as lead, nickel, or cadmium. Contaminants can be introduced to the soil though disintegration of underground storage tanks, addition of municipal sewage sludge, discharge of industrial waste, leaching of landfills, accidental spills, and smelter emissions.

The widespread use and disposal of harmful chemicals means there is the potential for these compounds to enter the food chain and damage the health of plant and animal species. Some pollutants in the soil are taken up initially by plants and burrowing soil organisms, where they accumulate in the body without breaking down. These plants and animals are consumed in large number by organisms higher in the food chain. As a result, the pollutants build up in progressively higher concentrations in organisms of higher trophic levels. This process is called *bio-magnification*. Due to bio-magnification, the impacts of soil toxins are most visible in organisms at the top of the food chain. In the long term, this accumulation of toxins can cause sickness, disease, reproductive failure, genetic defects, and in extreme cases, death.

A common example of soil contamination is the use of sewage sludge as a fertilizer. Though sewage is a rich source of the essential nutrients phosphorus and nitrogen, it can contain high concentrations of contaminants such as nickel, arsenic, zinc, and cadmium. Repeated applications of sewage sludge to soil can cause the buildup of these contaminants in the ecosystem with bio-magnification in humans and other animals high in the food chain.

Another common source of soil contamination is road salt. Though essential for the removal of snow, salt concentrations can build up along roadways causing stress and even death to plants and other vegetation.

Most symptoms of soil contamination only become visible over the long term as pollutants steadily accumulare to toxic levels. However, some sources of pollution are extremely concentrated, immediately causing detrimental ecosystem effects. Oil leaks, for example, occur when underground storage tanks deteriorate over time, releasing chemicals to the soil. These chemicals can be carried vertically and laterally throughout the soil profile, contaminating underground and surface drinking water sources.

8.7 Erosion

Erosion is the loosening, transport, and deposition of soil particles by wind, water, ice, or gravity. Erosion is in reality a natural phenomenon that occurs in equilibrium with soil formation, so that the net impact of soil loss is actually zero. Unfortunately, anthropogenic influences such as mismanagement of agriculture, deforestation, overgrazing, and unmanaged construction activity have upset the balance between formation and removal, causing immense loss of fertile topsoil. The results can be devastating. Accelerated erosion depletes soils necessary for agriculture and forestry activites and damages downstream lands, habitats, roads, dams, and waterways.

Erosion is one of most widespread forms of soil degradation. It occurs on almost all land surfaces, and impacts the biological, physical, and chemical properties of the soil both on-site and off-site.

8.7.1 Water Erosion

Water erosion is the detachment and transport of soil particles either directly by the impact of raindrops or indirectly by rapidly running water on the surface of soil. Snowmelt and rainfall are the primary driving forces behind water erosion.

Detachment occurs when the impact of raindrops causes soil particles to loosen and become dislodged from their original aggregates. The force of impact is determined by a combination of the weight of the rain droplet and its velocity. The energy of impact may create a forceful splash that will pick up and transport the soil an appreciable distance from its original location. Under conditions of heavy rain, the energy of impact is sufficient enough to displace soil particles by as much as 1-2 meters horizontally. However, rain splash usually only displaces particles by a few centimeters, this is called splash erosion.

Figure 28: The impact of a water droplet hitting the ground causes particles of soil to detach from the granule and be translocated (Plant and Soil Science eLibrary, 2015)

Compacted soils with poor water infiltration are at an increased risk of water erosion, because the soils become rapidly saturated and any additional water becomes surface runoff. Surface runoff exacerbates the effect of erosion. Bare soils are most vulnerable to water erosion since they lack the protection offered by vegetation. Plants, trees, and shrubs can absorb the impact of raindrops and prevent particle detachment.

Soils on slopes also frequently experience water erosion, since runoff gradually gains speed and energy as it moves down the slope

The agent most accountable for the translocation of soil particles is running water of runoff that flows at great velocity parallel to the surface of the soil and sweeps off valuable topsoil in its path. Moving water can withhold enough force to pick up and transport particles by floating, rolling, dragging, and splashing. Sheet erosion, rill erosion, and gully erosion are the most common types of water erosion. Mass erosion through slips and slumps occur less often, but can have catastrophic impacts.

Sheet Erosion

Sheet erosion occurs when water flows across the surface of the earth in thin unconfined sheets rather than in defined channels. Sheet erosion is caused by the flow of precipitation that is unable to penetrate through the ground, and instead flows above the soil as runoff. Sheet erosion does not carry sufficient volume or velocity to dislodge soil particles on its own; however, it can carry large quantities of particles that have been detached from their aggregates by splash erosion.

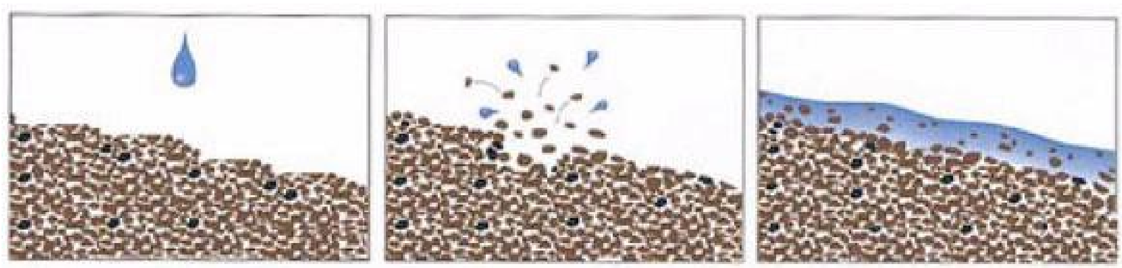


Figure 29: Detached soil particles are transported by runoff in the form of sheet erosion (Plant and Soil Sciences eLibrary, 2015)

Rill Erosion

Sheet erosion is difficult to detect until it evolves into rill erosion. Rill erosion occurs when sheet flow becomes concentrated and confined to a small streamlet. Water flows in narrow channels, on gently sloping lands, with enough strength to detach and carry away particles of soil from the bottom and sides of the channel. Contrary to sheet erosion, the concentration flow of rill erosion creates land features that are distinct and visible. Rill channels can be as deep as 30 cm and lead to the loss of the most productive part of the land.

Gully Erosion

Gully erosion is the advanced stage of rill erosion when the channels enlarge into deep ditches that are capable of eroding vast amounts of soil in a short period of time. Gullies usually occur near the bottom of slopes. They eat into the land, remove precious organic matter, and expose the subsoil beneath.

Slumps and Slips

Gullies expand by undercutting or slumping. Slumps and slips are both a form of mass erosion. Slumps are down-slope movement of land. Slips occur when the soil become so saturated with water that it can no longer stay intact. When a portion of the soil slides downhill, we say that a failure has occurred. Slips and slumps leave soils very susceptible to more gully erosion, and cause soil loss on a large scale.

Figure 30: Gully erosion. (Plant and Soil Science eLibrary,

Figure 31: Slump erosion.
(Plant and Soil Science eLibrary, 2015)

The rate and magnitude of water erosion is influenced by several factors. The intensity of precipitation is directly proportional to the rate of erosion. More intense precipitation carries more kinetic energy that is able to displace more soil. More runoff also occurs in the spring when large quantities of meltwater enter an already saturated system. Because water cannot seep through the soil, it flows above the soil, creating massive losses. The permeability of the soil affects it's ability to absorb water and soils with high permeability have less runoff. Texture is another factor that controls erosion. Soil textures that allow greater infiltration, have larger particle sizes, and are well aggregated are more resistant to erosion. Sands are generally heavier particles with higher porosity, and therefore are less prone to erosion. Soils high in clay and organic matter form strong aggregates and resist erosion. The most erodible soil textures are silt and very fine sand. Soil erosion by water also increases with slope length and steepness. Vegetation cover is perhaps the most important factor in minimizing water erosion. Vegetation can intercept falling raindrops and prevent the impact with the soil. Vegetation also slows down surface runoff and allows excess water to infiltrate the soil. Knowing about the factors that influence erosion has helped scientists create means of conserving soil by minimizing erosion.

8.7.2 Wind Erosion

Aeolian or wind erosion is most prominent in the world's drylands, particularly in areas with unconsolidated sediments, sparse vegetation cover, and turbulent winds. Wind erosion is the process by which soil particles are dislodged from the soil surface and carried a distance away from their original location by the kinetic energy of wind. Wind erosion is a normal agent in the formation of many of the world's landscapes. However, the magnitude of damage caused by wind erosion can be immense and cause serious destruction in many regions of the world. Globally, areas most affected by wind erosion include North Africa, Near East, the Siberian Plains, Australia, Northern China, North America, and Southern South America.

Soils exposed to wind erosion lose much of their fertile topsoil and denude the roots of crops and plants. In addition, the airborne soil particles can also obscure visibility and pollute the air, causing health and safety issues to humans and animals. Similar to water erosion, there are numerous means by which soil particles are eroded by wind.

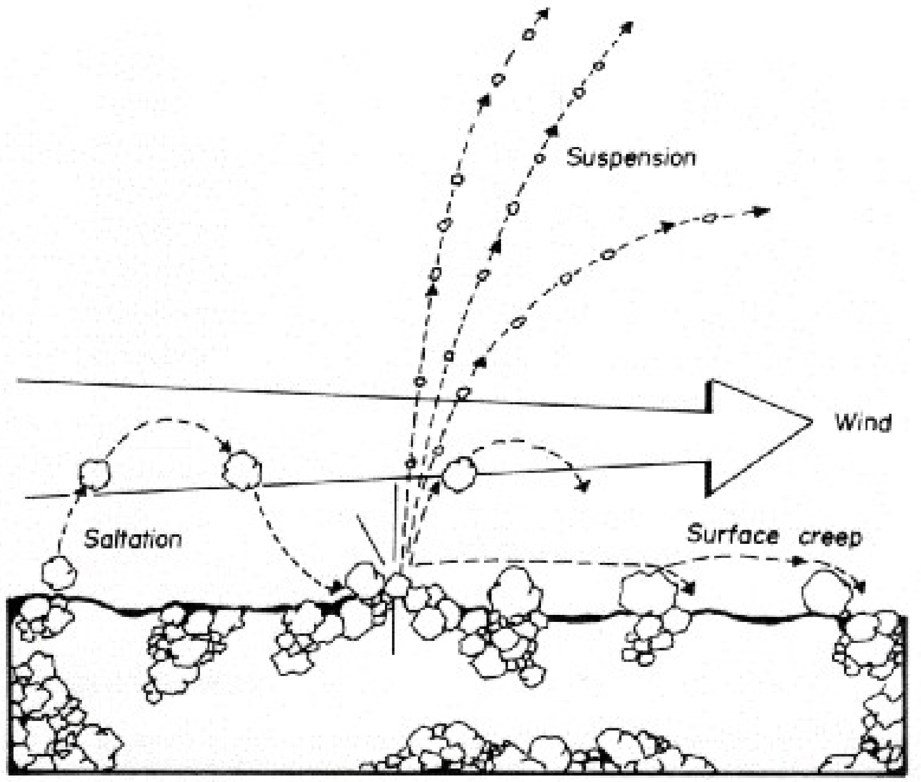


Figure 32: Types of wind erosion: saltation, surface creep, and suspension (Agronomy Guide, n.d.)

Creep
When wind travelling parallel to the surface of the ground strikes the surface, it causes soil granules to detach from the rest of the aggregates. The wind turbulence and velocity push particles forward. If the particles are too large to be picked up by wind, they roll along the surface of the ground. This is called creep. Creeping particles collide with other particles on the surface and set them into motion as well.

Saltation
Some soil particles are light enough to be picked up by wind turbulence, but not small enough to be carried large distances. These particles bounce up and down, moving short distances forward by wind. When the particles drop back to the ground, they collide with and dislodge other particles, giving them kinetic energy to move forward as well. This bouncing action is called saltation.

Suspension
If the soil particles are so fine and light that they can become *suspended* in the air, they may travel far distances, as much as hundreds of kilometres, and cross continental distances in the upper atmosphere. Fine dust from the Sahara Desert in Northern Africa has been shown to travel to as far as South and Central America by suspension. The airborne particles are eventually deposited to the ground with precipitation.

Figure 33: June 17, 1999. NASA's TOMS Satellite shows dust coming off regional land sources in Africa and travelling across the Atlantic Ocean. (Greenbelt, 2003)

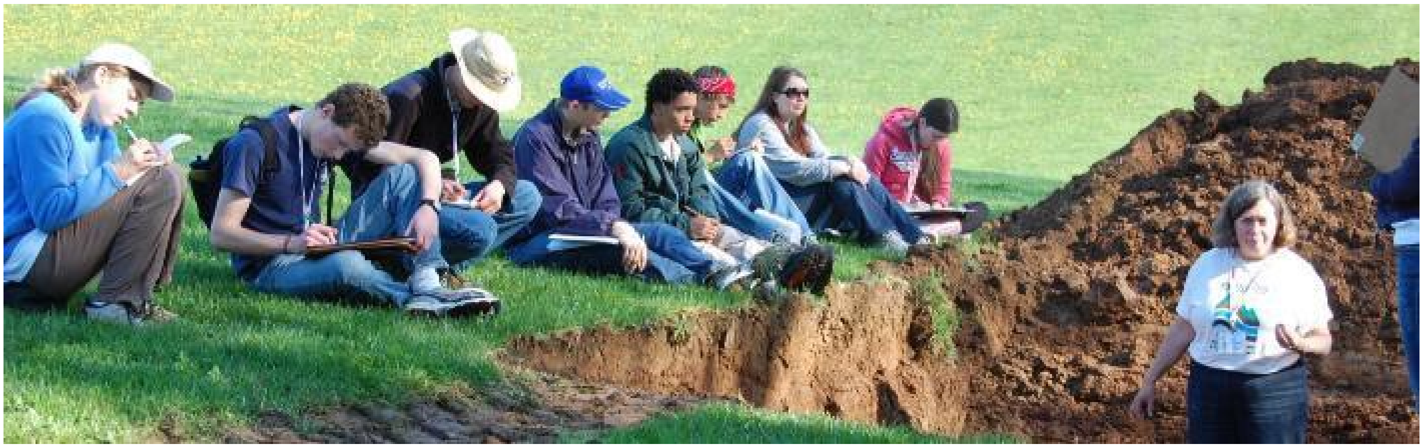
The rate and magnitude of wind erosion is controlled by five factors. Climate is the predominant factor influencing the rate of erosion. Windy regions with dry soil moisture regimes are most prone to erosion. The inherent erodibility of the soil refers to the ease with which particles can be detached and transported. Coarse soil particles such as sands are heavier and less prone to erosion. Very fine particles are highly cohesive and not easy to erode as well. Fine and medium sized particles, however, can be lifted and deposited relatively easily. Surface roughness influences wind erosion in that rough surfaces provide barriers against moving particles. Vegetation cover offers a similar protection barrier. Finally, the quantity of soil that is eroded depends on the length of exposed area. In large exposed areas the wind gains speed as it travels due to lack of obstacles. The rate and magnitude of erosion is enhanced as a result.

8.7.3 Economic Impacts

Erosion carries away organically rich topsoil, depletes nutrients, damages soil structure, and exposes more erodible subsoil. This is unfortunate, considering that it can take over two centuries to form just one inch of organic topsoil. Soil erosion presents a global crisis that threatens food security and sustainable agriculture and forestry.

The economic impacts of soil erosion are reflective of the terrestrial and aquatic damages done on and off the site of erosion. On-site costs of erosion are costs associated directly where erosion has occurred. The removal of nutrients, organic matter, and soil from land decreases the value of the property as well as the potential income from the land. Decreased yield due to removal of rich topsoil creates a need for the application of expensive fertilizers.

Soil erosion also creates indirect costs on both land and aquatic ecosystems away from the site of erosion. Off-site costs of erosion are generally a result of dust and air pollution, clogged drainage ditches, as well as sedimentation and pollution of water systems and fish spawning beds. When large quantities of nutrient-rich sediments are washed away and enter surface waterways, they can increase nutrient concentrations in the water which in turn increases algae growth. This process is called Eutrophication. When large algal blooms die, bacteria at the bottom of water bodies use up large quantities of dissolved oxygen to decompose them. This lack of oxygen is called hypoxia or anoxia and can destroy aquatic habitates and kill fish. The off-site impacts of erosion can include declining fish stocks and decreased recreational value of waterways. The consequences of erosion include increased costs to remove sediment from waterways improve water quality, of treat drinking water., Off-site costs of erosion can be higher than on-site erosion costs. In Ontario alone, approximately $91.2 million is spent annually to correct adverse off-site effects of soil erosion (FON and SWCS, 1995).



9.0 Soil Management and Conservation

9.1 Management Techniques

Soil conservation practices are diverse and target different types of soil problems such as erosion, saltation, acidification, and desertification. The first step to designing proper conservation techniques is to have a thorough understanding of the soil properties and the problems affecting the land. There are many reasons to practice conservation of the land. The Federation of Ontario Naturalists and the Soil and Water Conservation Society list ten reasons to practice soil conservation:

Ten Reasons to Practise Soil Conservation

1. **To maintain adequate amounts of organic matter and biological life in the soil.** These two components account for 90-95% of the total soil productivity.
2. **To ensure a secure food supply at reasonable prices.** It has been proven that soil conservation increases crop yields over the long term because it keeps topsoil in its place and preserves the productivity of the soil.
3. **To grow enough food.** Not only for ourselves but also for people in other countries, especially where there are food shortages.
4. **To save farmers money.** Erosion costs farmers millions of dollars each year in lost income as the loss of nutrients from the soil results in lower crop yields.
5. **To save citizens money.** Soil erosion costs taxpayers millions of dollars each year, especially related to off-site costs.
6. **To improve water quality and conserve water.** All forms of life require clean water to survive. Soil erosion is a major source of sedimentation and contamination of water supplies.
7. **To improve and conserve wildlife habitat.** Soil conservation practices such as the provision of buffer strips and windbreaks greatly enhance the quality of environment for wildlife of all kinds.
8. **To preserve natural beauty of the scenery.**
9. **To create or maintain an environment free of pollution where all life can live safely.**
10. **To ensure that our children will have sufficient healthy soils to support life into the future.** It has been said that the land has not so much been given to us by our forebears as borrowed from our children.

9.1.1 Six Practices That Improve Soil Performance

Improving soil performance requires different actions on each farm. Most soil-friendly farm practices fall into one of six groups. Each of these practices is further explained in other publications in the series.

1. **Adding organic matter**

   Regular additions of organic material may be the most important way to enhance soil quality. Organic matter improves soil structure, enhances water and nutrient holding capacity, protects soil from erosion and compaction, and supports a healthy community of soil organisms. Organic matter includes residue and roots from the previous crop, animal manure, cover crops, or amendments from off the farm.

2. **Avoiding excessive tillage and soil compaction**

   Tillage is valuable for loosening surface soil, preparing the seedbed, and controlling weeds and pests. But tillage can also break up soil structure, speed the decomposition and loss of organic matter, increase the threat of erosion, destroy the habitat of helpful organisms, and cause compaction. Reducing tillage minimizes the loss of organic matter and increases the residue protecting the soil surface. Compaction reduces the amount of air, water, and space available to roots and soil organisms. Compaction is caused by traveling on wet soil or by heavy equipment.

3. **Managing pests and nutrients efficiently**

   In this century, pesticides and chemical fertilizers have revolutionized U.S. agriculture. In addition to their desired effects, they can harm non-target organisms and pollute water and air if they are mismanaged. Nutrients from organic sources also can become pollutants when misapplied or over-applied. Efficient pest and nutrient management means applying only the necessary chemicals, at the right time and place to get the job done; testing and monitoring soil and pests; and adding non-chemical approaches to your management toolbox (such as crop rotations, cover crops, and manure management).

4. **Keeping the ground covered**

   Bare soil is susceptible to wind and water erosion, and to drying and crusting. Groundcover protects soil, provides habitats for larger soil organisms (such as insects and earthworms), and can improve water availability. Farmers often leave crop residue on the surface to cover the ground between growing seasons.

   Living cover crops create new organic matter and help feed soil organisms. Groundcover must be managed to prevent problems with delayed soil warming in spring, diseases, and excessive build-up of phosphorus at the surface.

5. **Increasing diversity**

   Diversity is beneficial for several reasons. Each crop contributes a unique root structure and type of residue to the soil. A diversity of soil organisms helps control pest populations, and a diversity of cultural practices reduces weed and disease pressures. Diversity across the landscape can be increased by using buffer strips, small fields, or contour strip cropping. Diversity over time can be increased by adding crops to the crop rotation or by varying tillage practices. Changing vegetation across the landscape or over time not only increases plant diversity, but also the types of insects, microorganisms, and wildlife that live on your farm.

6. **Monitoring soil performance**

Nothing can replace the value of "casual" observations of how your land is changing from day to day and year to year. Yet, to fine-tune management practices and promptly determine whether changes in soil or crops are significant, you also need to make systematic observations of the soil.

Source: http://www.extension.umn.edu/agriculture/soils/soil-properties/soil-management-series/introduction-to-soil-management/

9.1.2 Conservation Tillage and Cover Crops

Conservation tillage refers to a series of agricultural practices that attempt to prevent soil degradation by reducing (reduced tillage) or eliminating (no-tillage) the ploughing of the soil before sowing. Tillage can cause soil compataion, loss of organic matter, degradation of soil aggregates, death or disruption of soil organisms, and exacerbates erosion. In addition to changes in cultivation, conservation tillage also requires that plant residue is deliberately left on the ground rather than burning or incorporating it into the ground by ploughing. At least 30% of the ground must be covered by residue. Plant residue offers numerous benefits to the soil. First, it absorbs the impact of falling raindrops and slows down running water, thereby reducing water erosion. Since the surface of the soil is covered and protected, the incidence of wind erosion is less likely on conservation tilled soils. The roughness of the residue acts like a protective barrier that slows down the speed of wind. In addition, plant residues also help to conserve nutrients, add organic matter, improve water absorption and infiltration, slow down the rate of moisture evaporation, and conserve biodiversity.

Cover crops provide multiple potential benefits to soil health and the following crops, while also helping maintain cleaner surface and groundwater. They prevent erosion, improve soil physical and biological properties, supply nutrients to the following crop, suppress weeds, improve soil water availability, and break pest cycles. Some cover crops are able to break into compacted soil layers, making it easier for the following crop’s roots to more fully develop. The actual benefits from a cover crop depend on the species and productivity of the crop you grow and how long it’s left to grow before the soil is prepared for the next crop.

Grass cover crops are more likely than legumes to increase soil organic matter. The more residue you return to the soil, the better the effect on soil organic matter. The amount of residue produced by the cover crop may be very small, as little as half a ton of dry matter per acre. This adds some active organic matter, but because most of it decomposes rapidly after the crop is killed, there is no measurable effect on the total amount of organic matter present. On the other hand, good production of hairy vetch or crimson clover cover crops may yield from 1 1/2 to more than 4 tons of dry weight per acre. If a crop like winter rye is grown to maturity, it can produce 3 to 5 tons of residue.

Source: http://www.sare.org/Learning-Center/Books/Building-Soils-for-Better-Crops-3rd-Edition/Text-Version/Cover-Crops/Benefits-of-Cover-Crops

Figure 34: a) Conservation tillage, b) Cover crops (Wikipedia, 2015)

9.1.3 Crop Rotation

There are very good reasons for **Crop Rotation**. Rotating crops usually means fewer problems with insects, parasitic nematodes, weeds, and diseases caused by plant pathogens. Rotations that include nonhost plants are effective for controlling insects like corn rootworm, nematodes like soybean cyst nematode, and diseases like root rot of field peas. When specific soil diseases are present, the length of time between growing the same or similar crop may vary from relatively short (one to two years for leaf blight of onions) to fairly long (seven years for clubroot of radish or turnip). Also, the rotation should contain some crops that are nonhosts or actually suppress the disease. Root growth may be adversely affected when continuously cropping to any single crop (see figure 11.1). This means that the crops may be less efficient in using soil nutrients and added fertilizers. In addition, rotations that include legumes may supply significant amounts of nitrogen to succeeding crops. A legume harvested for seed, such as soybeans, provides little N for the following crop. On the other hand, a multiyear legume sod such as alfalfa may well supply all the nitrogen needed by the following crop. Growing sod-type forage grasses, legumes, and grass-legume mixes as part of the rotation also increases soil organic matter. When you alternate two crops, such as corn and soybeans, you have a very simple rotation. More complex rotations require three or more crops and a fiveto ten-year (or more) cycle to complete.

Rotations are an important part of any sustainable agricultural system. Yields of crops grown in rotations are typically 10% higher than those of crops grown in monoculture in normal growing seasons, and as much as 25% higher in droughty growing seasons.

Source: http://www.sare.org/Learning-Center/Books/Building-Soils-for-Better-Crops-3rd-Edition/Text-Version/Crop-Rotations

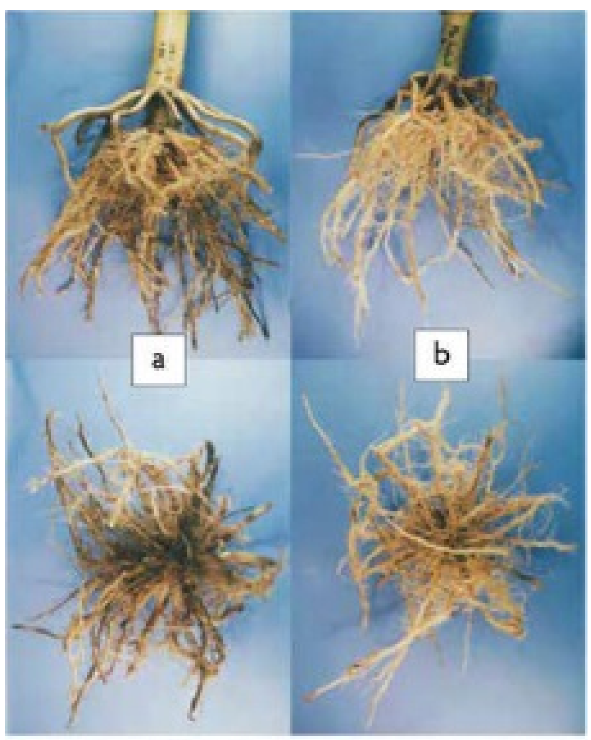


Figure 11.1 Corn roots: (a) continuous corn with mineral fertilizer, (b) corn following alfalfa with dairy manure compost. Photos by Walter Goldstein (Michael Fields Institute).

Figure 35: Crop rotation is a system of farming in which a regular succession of different crops is planted on the same land area, as opposed to growing the same crop time after time (Wikipedia, 2015)

9.1.3 Integrated Pest Management

Integrated Pest Management (IPM) is the integrated management of pest control by using cultural, biological and chemical methods. Using IPM best practices (e.g., surveillance of insect populations and understanding their life cycles as to when the populations are at their most sensitive to pesticide treatment) allows the farmer to reduce the number of pesticide treatments. Crop rotation is another means by which the population of pests can be reduced or eliminated. Other methods include the uses of pest-resistant crops, and biological controls such as the release of pest predators.

9.1.4 Vegetation Barriers: Conservation Buffers and Agroforestry

Conservation buffers are small strips of vegetation that are designed to manage environmental degradation. Examples of conservation buffers include windbreaks, riparian buffers, and grassed waterways. Windbreaks refer to trees or other forms of vegetation that are generally planted on the border of the farm. Riparian buffer strips are planted along rivers and water courses in order to prevent pollutants and sediments from entering water systems with runoff. Riparian strips also hold the soil to prevent slump erosion and create cooler habitats that are suitable for aquatic organisms including fish. Grassed waterways are permanently vegetated channels that are commonly used to prevent gully and rill formation by directing runoff water through land, to stable outlets such as streams. In contrast, **agroforestry** refers to a system of farming in which trees are planted in rows directly on the farm. The crops are integrated in rows or alleys between rows of trees.

Figure 36: a) Conservation buffer, b) Agroforestry (Wikimedia, 2007; Village Agroforestry, 2006)

9.1.5 Sediment control

Sediment control is important in areas that are prone to water and wind erosion. Two methods are used to control transport of sediments. **Silt fences** are used to slow down the rate of both wind and water erosion. These fences help to slow down the velocity of wind, similar to vegetation barriers. They are also able to filter out sediments that are transported with runoff, by allowing running water to pass through, but trapping sediments behind. Sediment ponds are ditches or depressions that hold large quantities of running water in one place, and prevent them from flowing away in channels. Over time, the sediments are able to settle to the bottom as the water evaporates. Use of this method prevents large quantities of fertile topsoil from leaving the ecosystem.

9.1.6 Acidification Control

Soils that are acidified to the point where production and yield are adversely affected can be corrected by the application of lime and other alkaline fertilizers. Though costly, these methods can help reclaim acid soils.

9.1.7 Salinization Control

Though it is difficult to reverse soil acidity, there are ways to manage soils that have been affected by salinity and sodicity. Here are some recommendations made by the Federation of Ontario Naturalists and Soil and Water Conservation Society;

- Summer fallowing of land should be decreased
- Deep-rooted crops that require high moisture levels should be grown in the groundwater recharge area
- Salt-tolerant plants should be planted in the salt-affected area
- Growing crops continually uses more water than summer fallowing
- When the amount of water entering the groundwater recharge area is decreased, the water table drops and there is less water available for soil salinization processes
- If salinization in caused by water from irrigation, tile drainage will remove the excess water and slow the salinization process. Irrigation canals should also be lined to prevent water seepage.

9.1.8 Combating Desertification

Combating desertification is best done through prevention efforts rather than rehabilitation and involves collaboration between governments, policy makers, scientists, and local residents. With a diversity of stakeholders and opinions involved, reaching agreements and solutions can be complex and tedious.

Effective prevention of desertification requires active land and water management strategies that protect against erosion, salinization, and other forms of soil degradation. Grazing of animals should be kept at a harmonious level with the carrying capacity of the land. Vegetation that protects the soil against wind/water erosion should not be harvested excessively for means such as fuel wood, grazing, or cultivation. Irrigation of soil in drylands should be kept to a minimum and done during the cooler periods of the day/night (see section on salinization control).

9.1.9 Sustainable Forest Management

Sustainable forest management is a way of using and caring for forests so as to maintain their environmental, social and economic values and benefits over time. Forest management planning is used to ensure that forests are managed sustainably and includes legislated forestry practices designed to protect soil and other ecosystem services that are linked to healthy soil (e.g, water quality, erosion protection, biodiversity).

Sustainable forestry practices pertaining to soil protection include guidelines on proper logging road construction (road locations, stream crossings, maintenance), harvesting operations (protected areas and areas of concern, timing of operations, harvesting system, slash management, renewal strategy), and hazardous materials (fuel handling, waste disposal). Guidelines for sustainable forest management are science-based and therefore best practices are regularly revised as new knowledge becomes available.

10.0 Glossary

Acidification: a decrease in the pH of the soil beyond those ranges tolerable by plants and soil organisms

Acidity: the level of acid in substances such as water or soil

Aeration: is the process by which air is circulated through, mixed with or dissolved in a liquid or substance.

Agroforestry: a system of farming in which trees are planted in rows directly on the farm

Alkalinization: an accumulation ofexcessive quantities of sodium at or near the soil surface due to evaporation

Bioaugmentation: the addition of living bacterial cultures required to speed up the rate of degradation of a contaminant

Biogenic: produced or brought about by living organisms.

Biogeochemical: relating to or denoting the cycle in which chemical elements and simple substances are transferred between living systems and the environment.

Biological Nitrogen Fixationis the process through which organisms convert nitrogen from the air (N_2) into a form of nitrogen that is available to plants

Bioremediation: use of biological agents, such as bacteria or plants, to remove or neutralize contaminants, as in polluted soil or water

Biostimulation: the modification of the environment to stimulate existing bacteria capable of bioremediation. This can be done by addition of various forms of rate limiting nutrients for example.

Capillary action: the tendency of a liquid in a capillary tube or absorbent material to rise or fall as a result of surface tension

Cation Exchange Capacity (CEC): a measure of the number of sites on soil surfaces that can retain positively charged ions (cations) by electrostatic forces

Chemical weathering: the breakdown of rock by chemical forces

Chroma: purity or intensity of color

Clastic: denoting rocks composed of broken pieces of older rocks

Clay: Mineral soil particles <0.002mm in diameter

Climate: the weather conditions prevailing in an area

Cobble: a coarse fragment found in soil 8- 25 cm in diameter

Colloid: fine particles of organic matter and clay that have a large surface area to volume ratio

Conservation buffers: small strips of vegetation that are designed to manage environmental degradation

Cover crop: a crop planted between periods of regular cop production to prevent soil erosion and provide humus or nitrogen

Crop rotation: the system of varying successive crops in a definite order on the same land, esp. to avoid depleting the soil fertility and to control weeds, diseases, and pests

Decomposer: an organism that decomposes organic material

Degrade: to lower in quality or value; make inferior or less valuable; in terms of geology it is to wear away by erosion or weathering.

Erosion: the gradual wearing away of something by natural forces (such as water, wind, or ice)

Detritivore: an organism, such as a bacterium, fungus, or insect, that feeds on dead plant or animal matter

Desertification: the process by which fertile land becomes desert

Extrusive: relating to or denoting rock that has been extruded at the earth's surface as lava or other volcanic deposits.

Fertility: soil that is rich in essential nutrients

Fine-textured: soils with a large percentage of small mineral particles (clays)

Gravel: a coarse fragment found in soil <8 cm in diameter

Groundwater: water held underground in the soil or in pores and crevices in rock

Herbivore: an animal that feeds only on plants

Horizon: a layer of soil or rock with particular characteristics

Hue: a color or shade

Humus: organic portion of topsoil

Igneous: having solidified from lava or magma

Infiltration: process by which water on the ground surface enters the soil

Intrusive (intrusion): the action or process of forcing a body of igneous rock between or through existing formations, without reaching the surface

Lava: hot molten or semifluid rock erupted from a volcano or fissure, or solid rock resulting from cooling of this

Lithification: is the process in which sediments compact under pressure, expel connate fluids, and gradually become solid rock

Loam: a textural class with a moderate mix of sand, silt and clay

Macrobiota: the series of organisms that is visible to the naked eye that digs the soil for shelter and feed on or in the soil

Medium: the substance in which an organisms lives

Mesobiota: include vertebrates such as mice, moles, and groundhogs and invertebrates such as ants, termites, earthworms and snails

Metamorphic: rock that has undergone transformation by heat, pressure, or other natural agencies

Microbiota: soil organisms 0.1-2 mm in diameter that generally live within the soil pores

Mycorrhizae: special group of fungi that live on or in plant roots and form symbiotic relationships with the plants

Nutrients: an element that provides nourishment essential for growth and the maintenance of life

Organic matter: matter composed of organic compounds that has come from the remains of organisms

Permafrost: a layer of soil that remains frozen throughout the year

Pedology: soil science

Parent material: the underlying geological material in which soil horizons form

Permeability: the state or quality of a material or membrane that causes it to allow liquids or gases to pass through it.

Physical weathering: the breakdown of rock by physical forces (i.e. ice, water and wind)

pH: a measure of the concentration of hydrogen ions in the soil

Plate tectonics: a theory explaining the structure of the earth's crust and many associated phenomena as resulting from the interaction of rigid lithospheric plates that move slowly over the underlying mantle

Plutonic: relating to or denoting igneous rock formed by solidification at considerable depth beneath the earth's surface

Precipitate: a solid material that emerges from a liquid solution

Primary consumer: an organism that that feeds on plants or other autotrophic organisms, also called herbivore

Primary producer: photosynthetically active organisms that produce biomass from inorganic compounds

Regolith: the layer of unconsolidated rocky material covering bedrock

Relief: the configuration of land in terms of its altitude and slope

Sand: mineral soil particles 0.05-2mm in diameter

Salinization: occurs when water soluble salts – sodium, potassium, calcium, magnesium, and chlorine – accumulate in excess concentrations in the root zone of plants to such an extent that they lead to degradation of soil and vegetation

Secondary consumer: an organism that feeds on primary consumers in a food chain

Sedimentary: rock that has formed from sediment deposited by water or air

Sequester: to remove or withdraw; to trap (a chemical in the atmosphere or environment) and isolate it in a natural or artificial storage area

Silt: mineral soil particles 0.002-0.05mm in diameter

Silt fences: temporary sediment control used to protect water quality from sediment in stormwater runoff

Sodicity: when salinization is due mainly to the concentration of excess sodium

Soil biota: organisms that spend all or a portion of their lifecycle within the soil or on its immediate surface

Soil profile: consists of the combined sequence of all the horizons in a soil

Stone: a coarse fragment found in soil > 25 cm in diameter

Subduction zone: sites of high rates of volcanism, earthquakes and mountain building

Taxonomy: the classification of something

Tertiary consumer: an organism that largely feeds on secondary and primary consumers

Texture: the percentages of sand, silt and clay in a particular soil sample. Can be estimated by the feel, appearance, or consistency of a soil sample

Texture triangle: a tool used to identify a soil textural class associated with various combinations of sand, silt and clay

Topsoil: the portion of the soil that acts as a growth medium for vegetation, providing humans and other animals with the food and a wild habitat.

Translocation: the movement of soil-forming materials up and down the soil profile

Transformation: the formation of arrangement of soil components into structural aggregates

Value: lightness of darkness of a color

Water-holding capacity: the amount of water a soil can hold

Weathering: the breakdown of rock by physical and chemical forces

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