Ontario Envirothon Study Guide

Ontario Envirothon

SOILS

This Study Guide is to be used to help Envirothon teams prepare for the Ontario Envirothon Program.

ONTARIO ENVIROTHON

Every year, more than 500,000 students, teachers and families take part in the unique learning experience of Envirothon. The program engages high-school students in learning more about four main areas of the environment—soils, aquatics, wildlife and forests. Students learn in the classroom and through interactive workshops aimed at strengthening scientific knowledge of our natural ecosystems, they develop foundational skills needed to pursue studies and careers in the environmental sciences.

The North American Envirothon, a program of the National Conservation Foundation, partners with organizations such as Forests Canada to coordinate events in which high school students receive training in essential resource management technologies and practices such as invasive species monitoring, habitat restoration, water and soil analysis, and forest management.

The program supports students in developing:

- A scientific understanding of natural ecosystems (soils, wildlife, forests, aquatics).
- Practical experience in resource management practices and technologies.
- The ability to apply scientific knowledge and creativity in developing innovative and sustainable solutions to major environmental challenges.
- Stronger communication, collaboration and problem-solving skills.

Acknowledgements

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Contents

Learning Objectives

Overall Objectives

Students must be able to…

A. Understand and describe the functions of soil in ecosystems and soil formation
B. Understand and describe the physical properties of soil
C. Understand and describe the chemical properties of soil
D. Understand and describe the biological properties of soil
E. Understand and describe soil water movement and content
F. Understand and describe the Canadian System of Soil Classification

Specific Objectives

Students must be able to…

A. Understand and describe the functions of soil in ecosystems and soil formation
1. Understand the importance of soil and its functions in ecosystems
2. Understand what soil is, and describe the rock cycle, glaciation and weathering
3. Understand and describe the soil forming factors and processes
4. Understand and describe organic and mineral soil horizons and their development

B. Understand and describe the physical properties of soil
1. Understand and describe soil colour using the Munsell soil colour system
2. Understand and describe soil texture and how it affects soil properties and behaviour
3. Understand and describe soil structure and why it is important to soil
4. Understand and describe soil bulk density and its relationship with soil pore space

C. Understand and describe the chemical properties of soil
1. Understand and describe soil colloids, cation exchange capacity and base saturation
2. Understand and describe soil pH and how it affects soil properties and plant growth
3. Identify soil macro and micro nutrients and how they are utilized by plants
4. Understand and describe nutrient cycles and the role of soil in recycling nutrients for plant growth

D. Understand and describe the biological properties of soil
1. Identify the types of macro, meso and microorganisms within the soil ecosystem
2. Understand and describe the relationship between soil organic matter and soil biodiversity
3. Understand and describe the functions of soil organisms
4. Understand and describe how soil organisms interact in the soil food web

E. Understand and describe soil water movement and content
1. Understand and describe the properties of water
2. Understand and describe the forces that affect the movement of water in soil
3. Understand and describe the role of macro and micropores in terms of soil drainage and water holding capacity
4. Understand and describe the types of soil water

F. Understand and describe the Canadian System of Soil Classification
1. Understand and describe the purpose of soil classification
2. Understand and describe the hierarchical categories of the Canadian System of Soil Classification
3. Understand and describe the diagnostic horizons used to determine soil Order
4. Understand and describe the soil Orders of Canada

Experiential Skills/Application/Analysis

Students must be able to:

1. Identify and measure soil horizons in a soil pit, photograph or sample
2. Describe and classify a soil profile using the Characterizing Sites, Soils and Substrates in Ontario and the Canadian System of Soil Classification
3. Collect soil samples using a soil pit or soil auger
4. Determine/measure and interpret the following soil properties:
    a. soil colour using the Munsell Soil Colour Charts
    b. soil textural class using the soil textural by feel method
    c. soil structure according to aggregate kind (i.e. single grain, massive, granular, blocky, prismatic or columnar and platy)
    d. soil bulk density
    e. soil pH using field test kits or a pH meter in the classroom
    f. soil macronutrient (i.e. nitrogen, phosphorus, potassium) levels using field test kits

Evaluation/Synthesis

Students must be able to:

1. Understand how soil mineral material, organic material, water and air are interrelated
2. Understand that productive soil is a limited non-renewable resource in human time frames and that preserving soil is an important issue
3. Use soil observations and data to recommend the suitability of a particular soil type for human activities
4. Use soil observations and data to make on-site recommendations on how to improve soil quality

2.0 Soil: The Producer, Protector, Connector

Most of us have had experiences with soil. Maybe it was making 'mud pies' as a kid, or maybe it was working in the family garden to grow beautiful flowers or tasty home-grown veggies. But in spite of our interactions with it, we often don't appreciate its importance to our lives. Humans rely on soil to produce the food we eat and protect the water we drink. Many people find that working in soil is calming and satisfying. We are truly connected to soil in so many ways!

2.1 The Importance of Soil

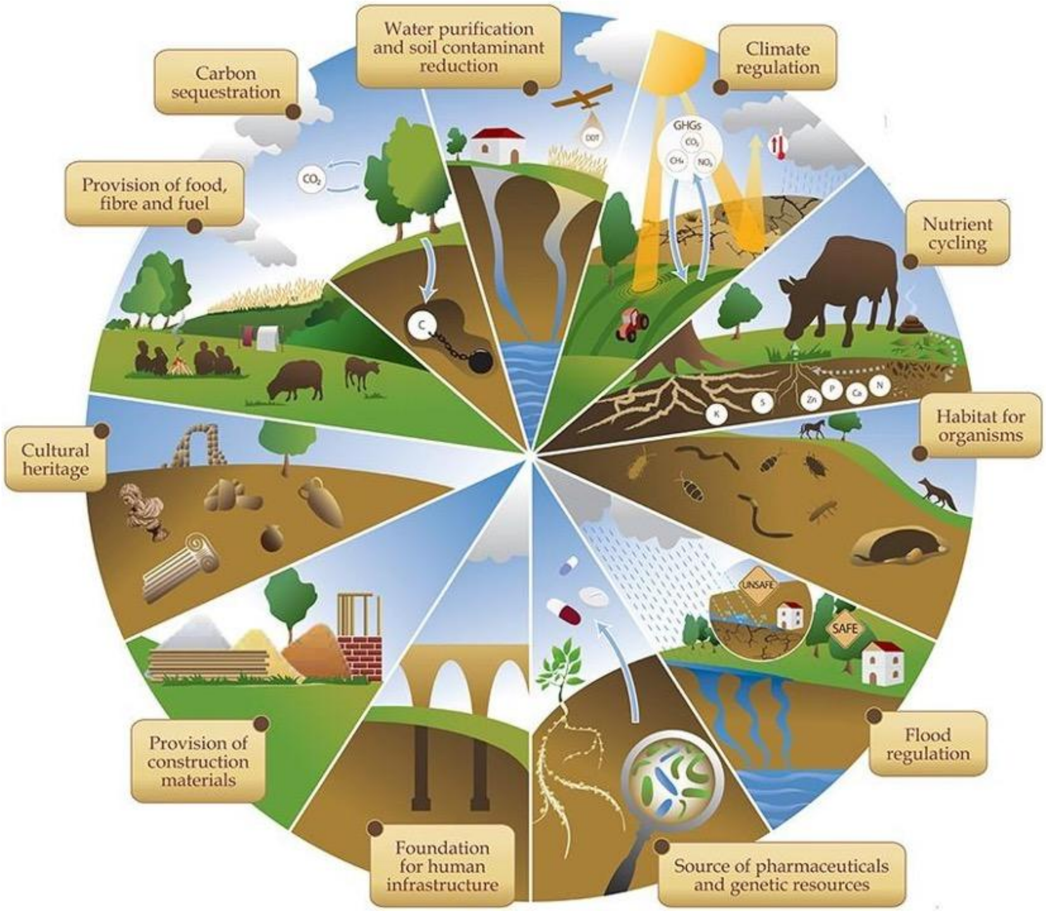


Figure 1: Soil functions. (Food and Agriculture Organization of the United Nations, 2015) https://www.fao.org/soils-2015/resources/infographics/en/

The soil functions shown in Figure 1 highlight most of the direct and indirect benefits soils provide to humans.

Soil functions that provide direct benefits to humans that are the easiest to recognize:

- FOOD: Agriculture and ultimately our food supply depend on healthy and productive soils. When you think about what you had to eat for breakfast today you can always trace its origin back to soil.
- FIBRE: Forests, which cover almost two-thirds of Ontario, also depend on soil. The fibre they provide is used as wood and paper products that we use in our daily lives.
- FUEL: Many people heat their homes with the fuel from forests in woodstoves, and woody biomass is increasingly becoming a source of renewable energy for community heating systems and electricity generation.
- WATER: We rely on soil to filter and purify the water we drink whether we get our water from a well or a surface water source like a lake or a river.
- WASTE: We use soil as a receptacle for our waste materials. Landfill sites are constructed with the idea that organisms in soil will decompose our garbage, and for those items that decompose slowly or don't decompose at all, that soil will act as a container to prevent hazardous materials from escaping into the surrounding environment.

Soil functions that provide benefits to humans that are less obvious and easily overlooked:

- FOUNDATIONS: We build houses, roads and office towers on soil. While we may take this soil function for granted, certain soil physical properties impact the suitability of soil for building structures and influence their long-term stability.
- MEDICINES: Soil is home to billions of microorganisms, and many of the antibiotics we use today to treat human infections were first discovered in soil. Bacteria and fungi that live in soil develop a myriad of chemical compounds to protect themselves and these compounds can be used to fight human diseases. Antibiotic-resistant microbes have become a major health issue and renewed research in soil-based antibiotics is a promising development to fight this problem.
- CULTURE: People across many provinces/territories, countries and cultures have a spiritual connection with soil. Soil can represent a sense of place and a connection to the land where someone was born or where they live based on its colour, smell or feel. In Canada we associate bright red soils with Prince Edward Island and dark fertile soils with the Prairie Provinces. In some cases, the cultural heritage of people is buried at specific sites and therefore the knowledge of their history is linked directly to the soil. An example of this in Canada is the discovery of subsurface anomalies at former Indian residential schools across the country. Using ground-penetrating radar archeologists have detected what they believe are unmarked graves of Indigenous children. In the Amazon River basin in South America archeologists and soil scientists have discovered black fertile soils called "Terra Preta". These man-made soils created with charcoal, pottery fragments and human waste produced crops that supported civilizations that existed thousands of years before European settlement.

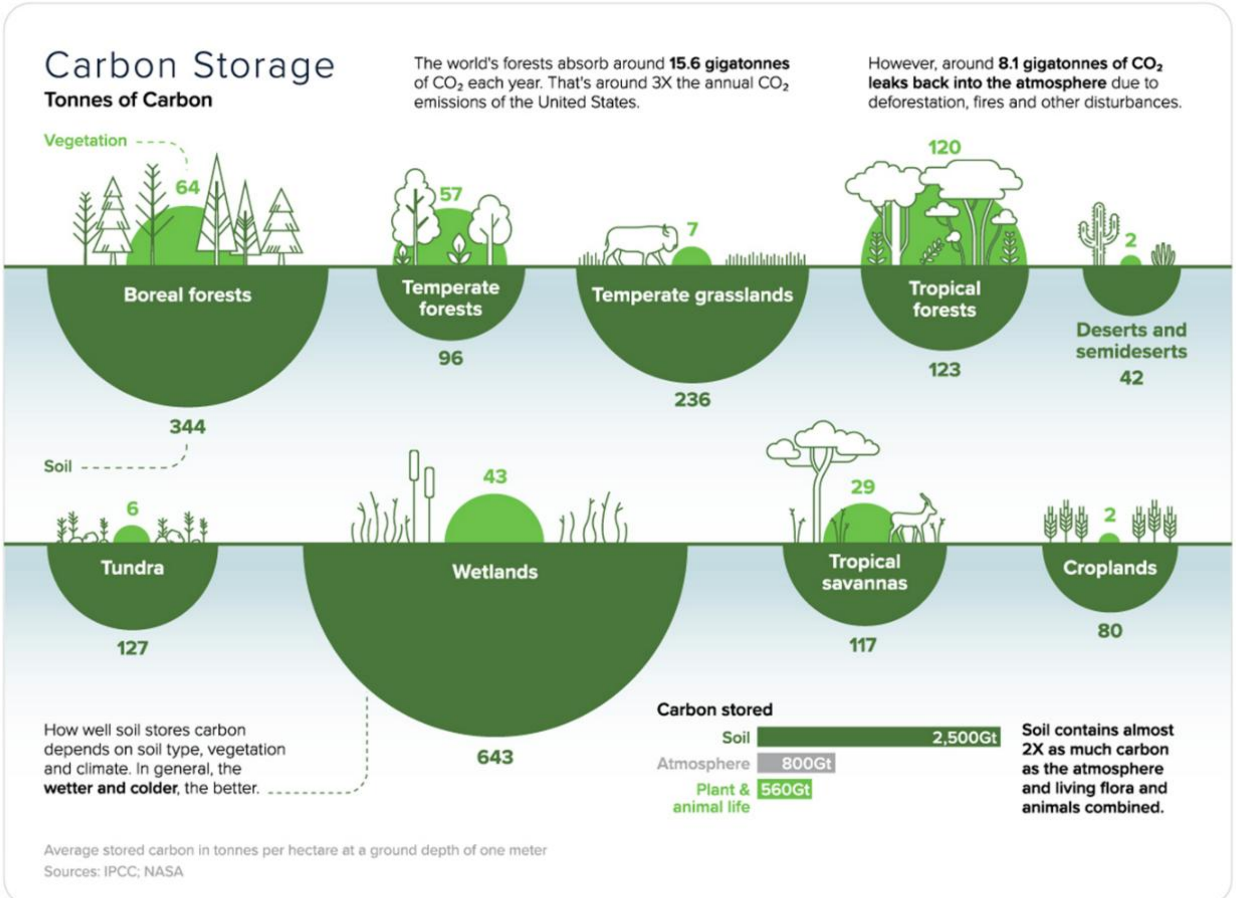


Figure 2: Ecosystem carbon storage. (Carbon Streaming Corporation, 2021) https://www.visualcapitalist.com/sp/visualizing-carbon-storage-in-earths-ecosystems/

Soil functions that provide indirect benefits in its role as part of the planet's ecosystems.

- LIFE: Soil is habitat, the place where many organisms live. The **nutrients** required by all the plants and animals on Earth are cycled through the soil through complex food webs. The storage of water in soil is a critical component of the water cycle and the reservoir of water in soil supports life on Earth.
- CLIMATE: Soil can store carbon, keeping it out of the atmosphere (see Figure 2). We now know that soils store almost twice as much carbon as the atmosphere and all the vegetation and animals combined! Ecosystems that are colder and wetter store more carbon in soil than warmer and drier ecosystems because of slower activity of organisms that decompose **organic matter**. Maintaining and enhancing soil carbon storage, or another way to say that, using soil as a "sink" for atmospheric carbon dioxide, holds promise as a solution to climate change.

2.2 Soil as an Ecological Unit: Pedosphere linkages

The earth's major subsystems, or spheres, interface with each other through the pedosphere (Figure 3). Soil (the pedosphere) links air (the atmosphere) and living things (the biosphere) to rocks (the lithosphere) and water (the hydrosphere) resulting in a productive and complex environment. At the landscape (kilometers) and plot (meters) scale, soil is the transition zone between bedrock and air, and provides water to plant roots. Organic matter from dead plants and animals is stored in the soil. At smaller scales (millimeters and micrometers) tiny mineral and organic soil particles provide surface area that attracts nutrients and water and supplies microhabitat for organisms. The pedosphere is central to the functioning of healthy, productive ecosystems on earth.

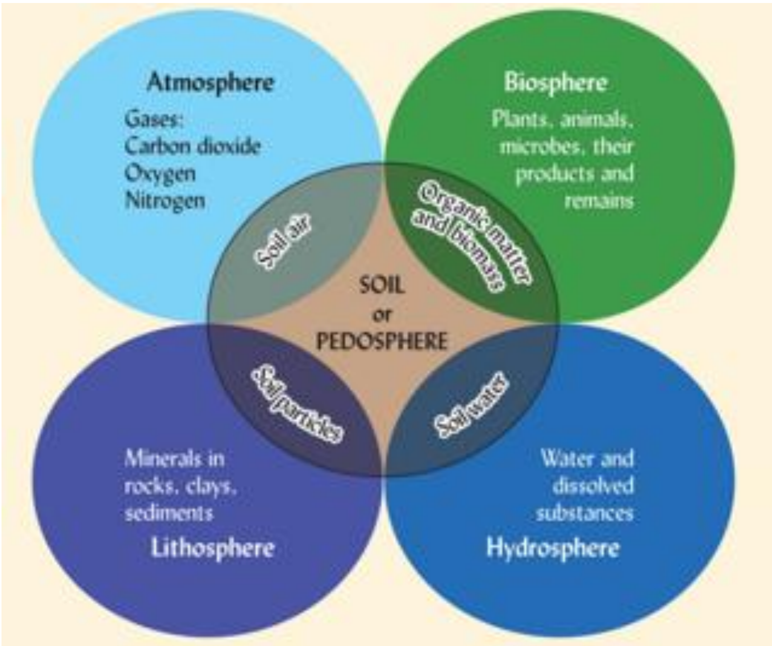


Figure 3: Soil (Pedosphere) linkages. (Weil and Brady, 2017)

2.3 What is Soil?

Soil is a non-renewable natural resource. The process of **weathering**, which is the breakdown of rocks into the mineral part of soil, can take thousands of years, and the incorporation of organic material into soil from the decomposition of plants is also a slow process.

After several years of discussion and debate soil scientists arrived at a new updated definition of soil in 2017. The previous definition had only considered soil on Earth but exploration by remote-controlled vehicles on Mars and soil sampling there in recent years had indicated there was no reason to limit soil to planet earth. The older definition only referred to the solid phase of soil and had also focused on the soil-forming factors rather than simpler terms related to physical, chemical and biological processes.

The new definition of soil is:

"The layer(s) of generally loose mineral and/or organic material that are affected by physical, chemical, and/or biological processes at or near the planetary surface and usually hold liquids, gases, and biota and support plants."

By including that soil "usually hold liquids, gases, and biota and support plants" the new definition clearly identifies all the possible components of soil but allows for flexibility. For example, desert soils on Earth and extra-terrestrial soils like those on Mars do not have plants.

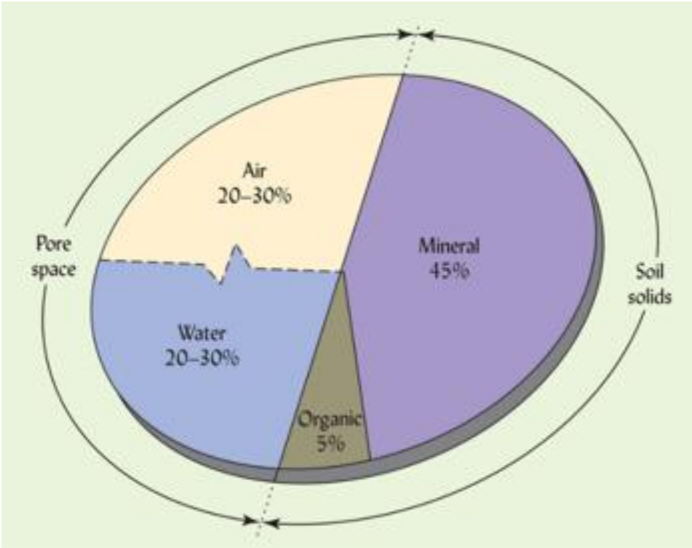


Figure 4: Volume composition of a surface mineral soil. (Weil and Brady, 2017)

Soil is not just solid matter. A surface mineral soil is a mixture of 45% mineral materials, 5% dead and living organisms (organic materials). Water and air, together known as the pore space, total the other 50%. The broken line between air and water in Figure 4 indicates that the proportions of these two components fluctuate as the soil becomes drier or wetter. The roots of plants need the pore space to grow and the water and air that circulate there are required by plants. The solid components, mineral and organic materials, contribute nutrients to plants and soil organisms. The interaction of these four components is what makes soil such an amazing natural resource and so dynamic in terms of the functions it fulfills.

2.4 The Study of Soil Science

Soil science is the study of soil as a natural resource. The historic branches of soil science study include pedology and edaphology.

- Pedology is the study of soil in its natural environment and examines the origin and formation of soil, what a **soil profile** looks like and the classification of soils.
- Edaphology is the study of how soils interact with living things. The focus of edaphology is on soil as a habitat for organisms and a medium for plant growth.

Due to the significant role that soils play across a broad range of environmental topics and issues, knowledge of soils is required in many disciplines. Soil science is an important area of study in the fields of engineering, agronomy, forestry, resource management, land-use planning, climate change, ecology, environmental pollution and archeology. Professionals associated with the study of soil include geologists, hydrologists, chemists, GIS and remote sensing specialists, biologists, microbiologists, environmental technologists and foresters. Knowledge that is essential to understanding soil also comes from many people that are not identified as soil scientists. Indigenous Elders, traditional Knowledge Keepers, farmers and individuals that have lived close to the land have used local observation and practices to build a relationship with soil.

2.5 Discussion Questions

1. Describe an experience you had with soil
2. What do you think is the most important soil function? Justify your response.

3.0 Soil Formation

Soil is everywhere but with poor land management soil can be washed away by **erosion** and its **fertility** can be lost. The degradation of soil can occur in just a few decades, compared to the thousands of years it takes to form a few centimeters of healthy, productive soil. Since soil formation takes so long compared to the time for degradation to occur, fertile soil is considered a non-renewable natural resource in human time scales. This is another reason why soil is so valuable.

3.1 Where Does Soil Come From?

Soil is formed from **parent materials** and this process is called pedogenesis. Pedo is Greek for soil and genesis means creation or birth. For any particular soil, at any specific location, the parent material is like the mother and father of the soil. The physical and chemical properties of the parent material are reflected in the attributes of the newly formed soil.

Parent material is the material created from the breakdown and disintegration of underlying bedrock or, in most cases in Canada, it is deposits left from glaciers that covered the land as recently as 12,000 years ago. Glaciers ground up the bedrock and transported soil parent materials great distances by ice, glacial meltwaters and wind. Parent materials are **sediments** and can range in size from boulders and gravel to smaller **sand**, **silt** and **clay**. Over time, natural forces of weathering facilitated by the sun and rain, and the presence of plants and animals transform the parent material into soil and develop a soil profile with different **horizons** (see Figure 5).

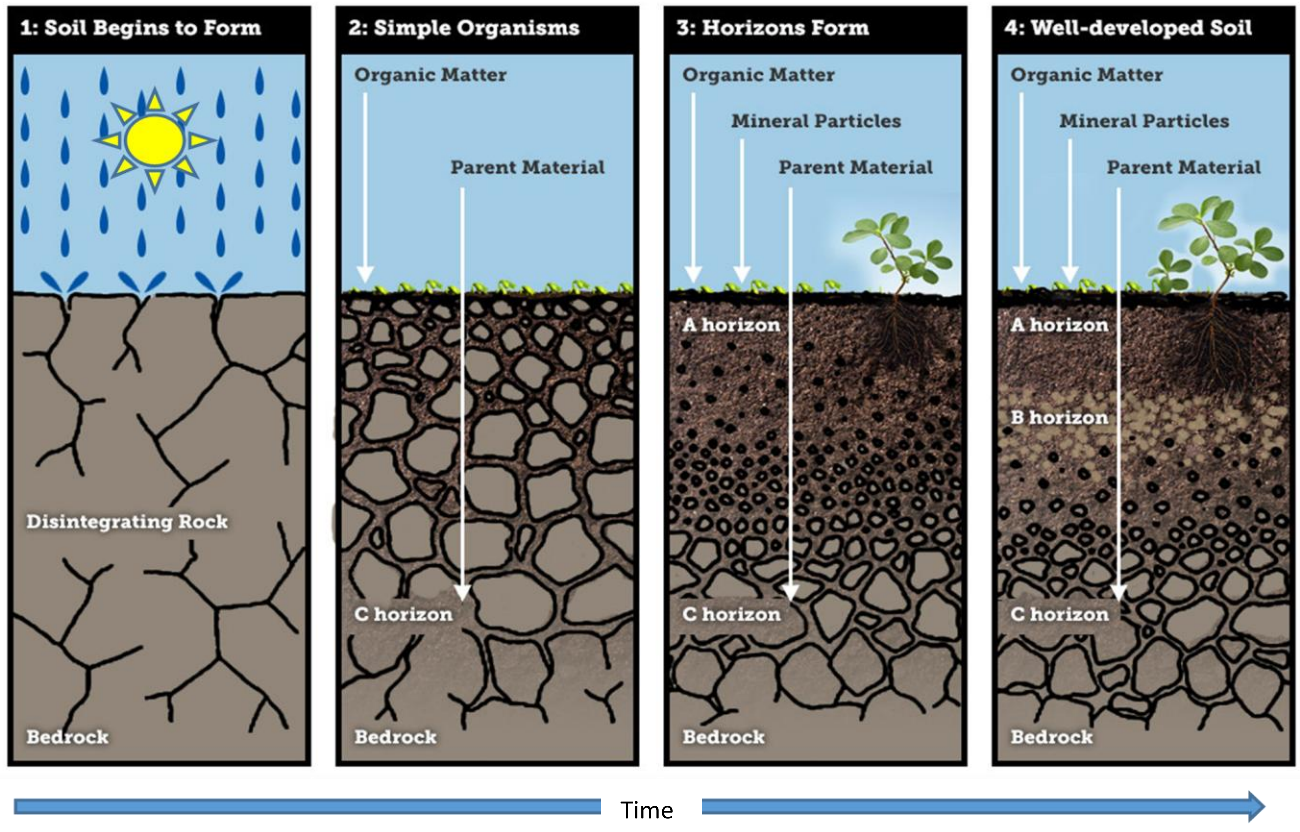


Figure 5: Soil development over time. (adapted from WeatherStem, 2017) https://learn.weatherstem.com/modules/learn/lessons/85/06.html

3.2 The Rock Cycle

Since the rocks and minerals that make up bedrock and glacial deposits can be the source of parent material for soil, which eventually becomes soil itself, it is important to understand how rocks form and transform. The rock cycle summarizes these changes (see Figure 6).

Rocks are classified according to how they are formed and by their mineral composition, as either **igneous**, **sedimentary** or **metamorphic**. The rock cycle does not necessarily start at any one of these rock types or proceed in any specific order. Rather, it can go from any rock type 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.

- Igneous rocks are called primary rocks and are formed when magma, that is rock which has been liquefied under the intense temperature and pressure inside the Earth, cools and becomes solid. Magma that cools slowly under the Earth's crust forms **intrusive** igneous rocks, while magma that erupts above the surface of the Earth cools rapidly to form **extrusive** igneous rocks.
- Sedimentary rocks are formed from **sediments** weathered from other rocks that are compacted and cemented together.
- Metamorphic rocks are formed when sedimentary or igneous rocks become buried deep below the Earth's surface and are physically and chemically altered by heat and pressure.

In time, igneous, sedimentary and metamorphic rocks become exposed at the surface of the Earth and experience new environment conditions; different pressures, moistures, temperatures and the presence of vegetation. Unable to tolerate the new environmental conditions, different from those under which they were formed, rocks disintegrate into sediments which are the inorganic mineral matter that in time forms soil. This is a key step in soil formation.

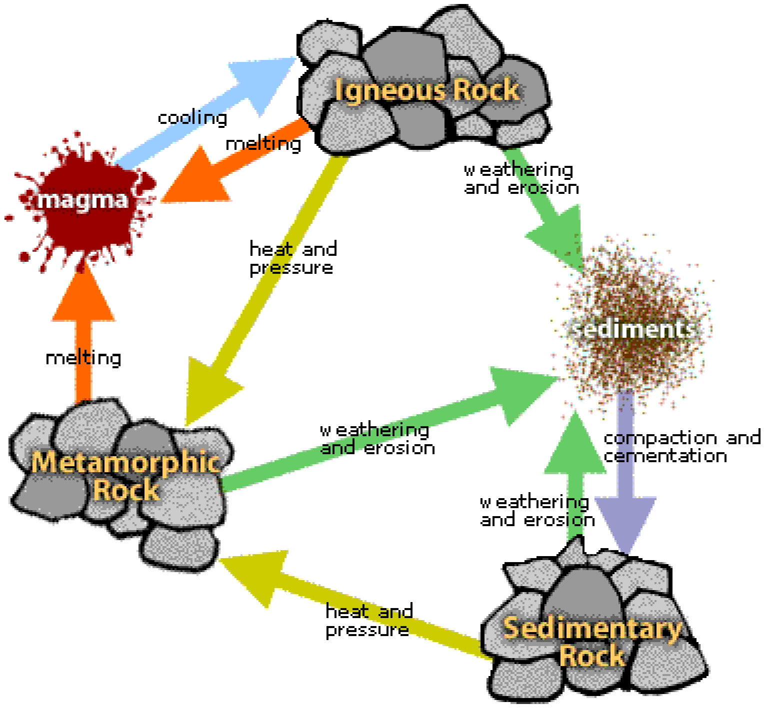


Figure 6: The rock cycle. (Earth Floor, 2005)
http://www.cotf.edu/ete/modules/msese/earthsysflr/rock.html

3.3 Glaciation

Glaciation is the formation, advance and retreat of glaciers. Glaciers are a mass of ice that develops when an accumulation of snow is greater than the rate of melting. The snow turns to ice and then begins to flow because of the downward pressure of the great mass of ice which can be up to three kilometers thick. Glaciation in Canada created the landscape features, like hills and valleys, and lakes and rivers, that we see today and is responsible for creating the parent materials that soils have formed from. The great ice sheets pulverized the bedrock and ground it into smaller particles that were eventually deposited in different ways across the land.

There are three major types of glacial deposits (see Figure 7).

- Glacial till or morainal: formed by moving or melting ice and are characterized by unsorted materials of all particle sizes, a mixture of sand, silt, clay and all sizes of coarse fragments, including boulders, stones, cobbles and gravel. The coarse fragments are angular with sharp edges. Glacial tills are essentially materials that dropped out of the glacier as it melted.
- Glacio-fluvial: sediments created by rivers as the glaciers melted. The glacial melt waters were fast moving and carried larger particles such as sands and gravels. In contrast to the shape of coarse fragments in glacial till, glacio-fluvial gravels have rounded edges due to the action of water. The meltwater also sorted the sediments and left layered, stratified deposits across relatively flat landscapes.

- Glacio-lacustrine: glacial meltwaters were restricted and trapped in front of the receding glaciers forming glacial lakes. Fine sand, silt and clay were deposited in these stiller lake waters. In addition to consisting of smaller particles these deposits are also layered due to action of water and have no coarse fragments.

The different glacial landforms and sediments provided the starting point as parent material for the distinctly different soils that have developed across Canada.

Figure 7: Examples of glacial sediments a) glacial till b) glacio-fluvial c) glacio-lacustrine. (adapted from Panchuk, 2021) https://pressbooks.bccampus.ca/physicalgeologyh5p/chapter/17-3-glacial-deposits/

3.4 Weathering

Weathering is the first step towards soil formation as rocks and minerals are physically broken down into smaller particles and chemically altered.

- **Physical weathering** refers to the disintegration of rocks and minerals by ice, water and wind without affecting their composition. Glacial ice embedded with soil and rock fragments gouges and grinds rocks in its path. Water movement causes abrasion between solid particles and windblown dust can wear down rocks acting much like sandpaper. Temperature changes caused by sunlight or wildfire can also cause the physical breakdown of rocks due to expansion of their component minerals. Some minerals expand more than others breaking the rock apart. Plants and animals can also physically crack rocks through rooting action or burrowing.

- **Chemical weathering** involves chemical reactions such as **carbonation, hydrolysis** and **oxidation** that release soluble materials and form new minerals from rocks. Water and oxygen are important to chemical weathering reactions. The dominant control of chemical weathering is the **pH** of the soil water in contact with minerals. More acidic water leads to the rupture of chemical bounds in minerals through hydrolysis. Chemical weathering is also enhanced by acids released by plant roots and soil microorganisms.

The creation of a weathered, unconsolidated/loose, heterogeneous/mixed parent material is the amazing process that precedes, or more commonly, occurs at the same time as the development of soil horizons we see when we dig a soil pit at any location.

3.5 Soil Forming Factors

Early soil scientists noted similar profile characteristics in soils that were located far apart from each other and contemplated why this was the case. In other situations they observed large differences in the appearance and properties of soil profiles from locations that were very close together. These investigations and subsequent studies led to the identification of the five natural soil forming factors, summarized as CLORPT, the soil forming equation.

Soil is a function of:
CL represents Climate – precipitation and temperature
O represents Organisms – plants and animals
R represents Relief – topography or shape of the landscape
P represents Parent Material – material from which the soil is formed
T represents Time – period of time over which the soil is formed

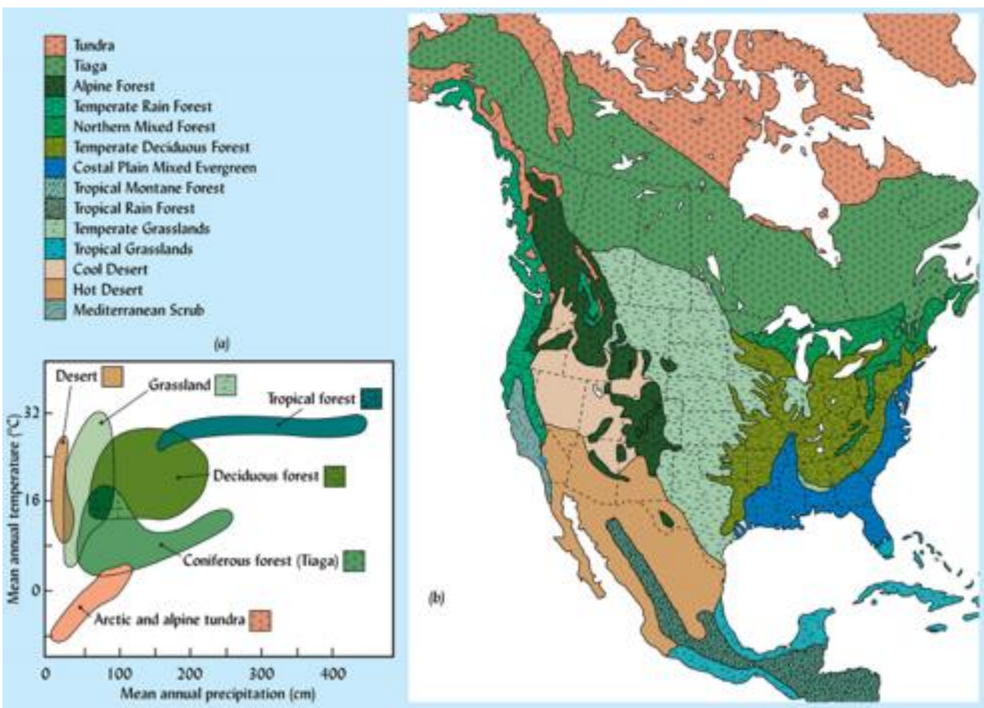


Figure 8: Effect of climate on vegetation. (Weil and Brady, 2017)

CLIMATE: The two most significant **climate** variables are temperature and precipitation. As temperature and precipitation increase, so does the rate of weathering. Climate influences vegetation type and growth (see Figure 8). Temperature and moisture control the rate of biological activity by soil organisms and therefore the rate of decomposition of organic matter.

ORGANISMS: Organisms include both vegetation such as plants and trees, and animals including **macrobiota**, **mesobiota** and **microbiota**. Different vegetation types provide varied organic matter inputs to soil which has an effect on soil formation. For example, litter inputs in a deciduous forest in Ontario would consist mainly of leaves and this would create very different physical, chemical and biological conditions in the soil compared to litter inputs with grassland vegetation found in the Prairie Provinces. Soil organisms are responsible for the process of organic matter decomposition, converting nutrients in organic matter into forms that can be taken up by plants and mixing the soil by burrowing. The soil food web is the community of organisms that live in the soil and the community makeup will be different at different locations depending on the other soil forming factors.

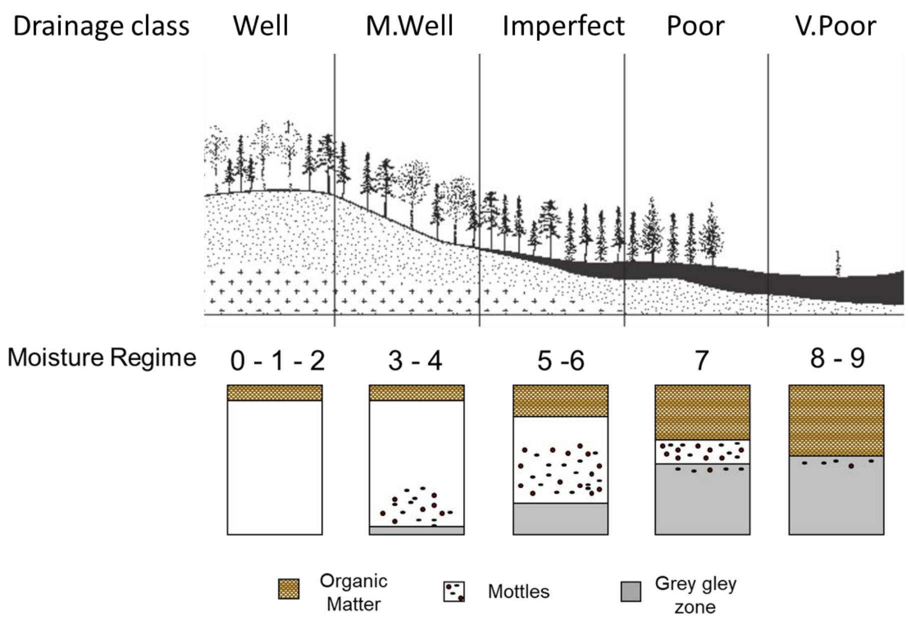


Figure 9: Effect of relief on drainage class and soil development. (adapted from Ontario Centre for Soil Resource Evaluation, 1993)

RELIEF: Relief, or topography, refers to the configuration of land in terms of its elevation, slope and landscape position. Landscape position controls water movement and soil moisture with better drainage and drier soils at upper, compared to lower, slope positions (see Figure 9). Profiles that are poorly drained exhibit features such as **mottles** and **gleying** due to the influence of the water table. The steepness of slope and the slope aspect, that is what compass direction the slope is facing, can also influence soil development. In the Northern Hemisphere, south-facing slopes receive greater exposure to sunlight and therefore experience warmer and drier microclimates than north-facing slopes. Removal of surface soil due to landslides and erosion on steeper slopes inhibits the accumulation and development of soil.

PARENT MATERIAL: As described in Section 3.1 parent material is the mineral material from which soils develop. The type of parent material influences the rate of soil formation, since some minerals are more resistant to weathering than others. The properties of parent material can also determine the physical and chemical attributes of a soil. For example, soils formed from limestone parent materials are finer textured, have a higher pH and higher concentrations of several important plant nutrients, than those derived from granite.

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 fertile soil. It can take thousands of years for a few centimeters of soil to develop from parent material. Mature soils are deeper, and have better defined and more developed horizons than younger soils. Due to glaciation, soils in Ontario are considered to be young, only 12,000 years old, when contrasted with mature soils in unglaciated terrain which can be up to 1,000,000 years old.

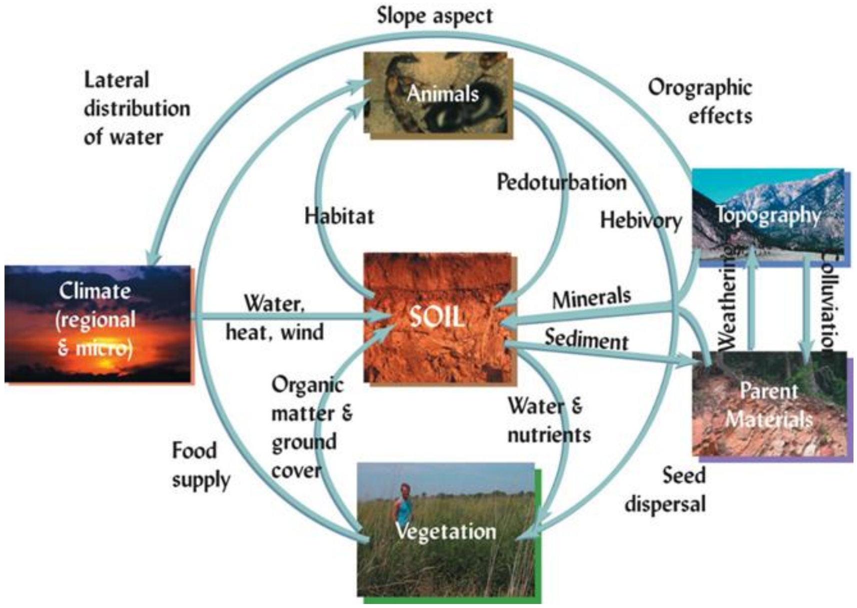


Figure 10: The integrated work of the climate, organisms (vegetation and animals), relief (topography) and parent materials on soil formation. The influence of these factors is modified by time but time as a soil forming factor is not shown. (Weil and Brady, 2017)

Understanding the five soil forming factors helps to better understand why soils differ from place to place, but it is important to realize that they do not act independently. They are linked in many ways and influence the formation of soils and development of soil profile properties in concert (see Figure 10).

HUMANS: It has always been recognized that human activities have influenced soil formation. Tilling, irrigating and fertilizing in agriculture, and urbanization are just a few examples of human interventions that drastically affect soil development. While the human factor was originally included as part of the organism soil forming factor there has been an ongoing debate in the soil science community for several decades to consider humans as a sixth soil forming factor. More recently it has also been accepted that human effects have become so widespread that they also directly affect each of the natural soil forming factors. Human caused climate change and the extent to which man-made materials have been used as fill to create new soil are just two of the many examples of how humans are having a major influence on soil formation.

3.6 Soil Forming Processes

During soil formation, the parent materials are modified by five fundamental soil forming processes. Soil horizons evolve through the addition, mixing, translocation, transformation and removals of soil particles.

- Addition includes organic matter dropped by vegetation as litter, water from rain, air, and energy from the sun.
- Mixing occurs through actions such as burrowing animals and frost heaving, the movement of soil due to freezing.
- Translocation refers to the movement of organic and inorganic materials laterally, or up and down in the soil profile usually due to water movement.
- Transformation happens when soil materials are physically or chemically modified or created from other materials. This includes the organic matter decomposition and the formation of aggregates when individual soil particles come together to form soil structures.

- Removal includes the evaporation of water, leaching of nutrients to ground or surface water and erosion of soil particles.

3.7 Soil Horizon Development

Over time, parent materials begin to differentiate vertically, giving rise to soil and displaying distinct horizons. A horizon is a specific layer in the soil that runs approximately parallel to the ground surface and has different properties from horizons above and below. Soil horizons vary in physical, chemical and biological properties. Although each soil has at least one horizon, the more mature soil is, the more differentiated its horizons are.

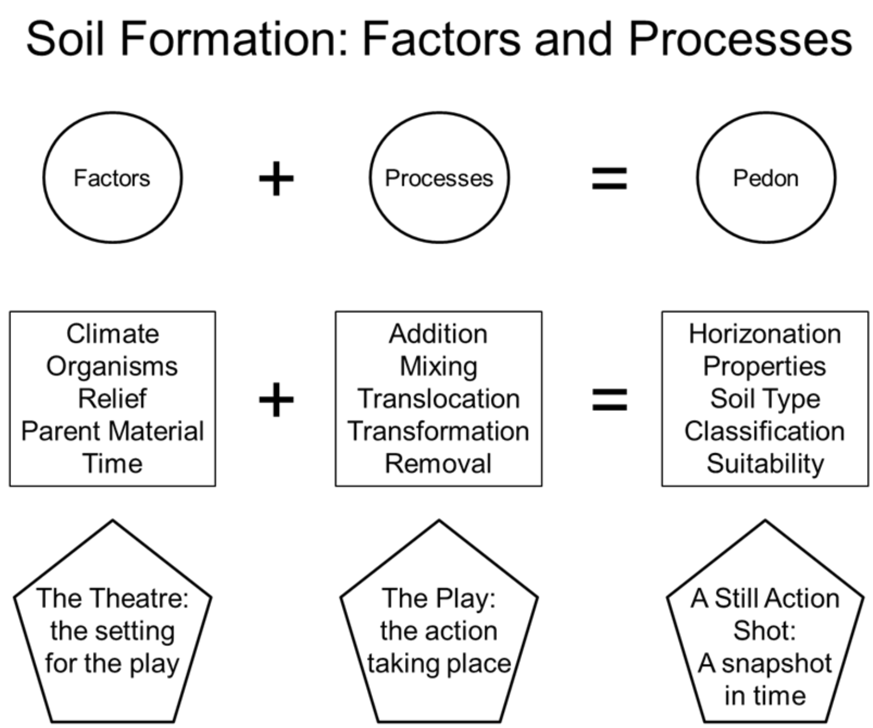


Figure 11: The factors and processes of soil formation. (adapted from Hutchinson, 1965)

At each specific location on Earth, soil horizon formation is a function of a particular combination of the influence of the five soil forming factors (Climate, Organisms, Relief, Parent Material, Time) and the five soil forming processes (Addition, Mixing, Translocation, Transformation, Removal) (see Figure 11).

The soil forming factors can be pictured as the theatre for a play, setting the stage for soil formation. The soil forming processes represent the play itself, the actions taking place in the soil modifying the original parent material and changing the soil profile over time. When we look at a soil profile we are looking at a still action shot from the play, essentially a snapshot in time of soil properties, the interactive effect of soil forming factors and processes that have occurred up to that moment in time. Human intervention can change the setting or actions in the play, resulting in differences in soil horizon development. Soil forming factors and processes combine to affect the soil profile which is sampled and described as a **pedon**.

The soil horizons present in any particular profile are differentiated and named according to their properties (thickness, colour, **texture**, structure, chemical and biological properties of horizons). The master soil horizons are designated using capital letters (see Figure 12). Subhorizon distinctions within the master horizons are labeled by adding lowercase suffixes to the master horizon capital letters (see Figure 13). The designations described here are representative of the **taxonomy** of the Canadian System of Soil Classification. Many countries have their own national soil classification systems that use different taxonomies from the Canadian system. National systems have better application to the soils within a particular country than an international system. When researching information online it is important to realize that many websites reference soil horizon designations from classifications other than the Canadian system, most frequently the United States soil taxonomy.

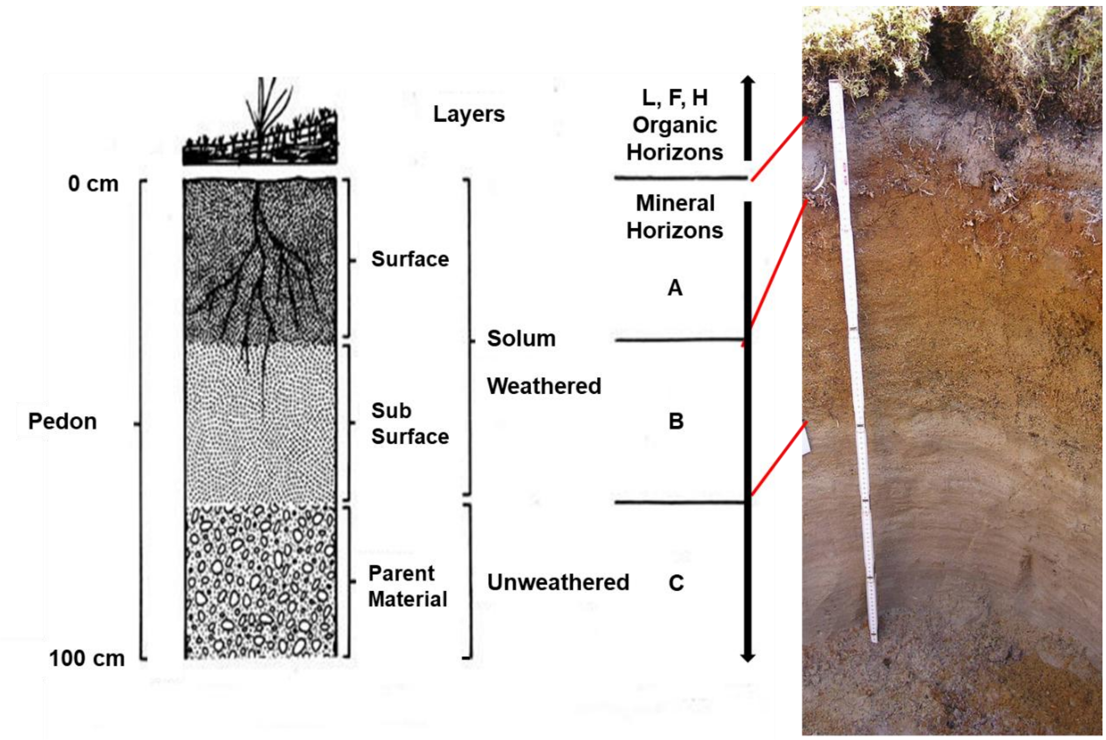


Figure 12: Master soil horizons of an upland forest soil. (adapted from Ontario Centre for Soil Resource Evaluation, 1993)

3.8 Organic Horizons

Organic horizons occur at the surface of upland mineral soils and in wetland soils. They contain more than 30% organic matter and are generally distinguishable by their dark colour. Two groups of these horizons are recognized:

- L, F, H horizons: upland soils, litter and woody debris (see Figure 13 b,d and 14 a,b). Also referred to as the forest floor horizons or duff.
  In well drained soils (upland areas) organic horizons develop primarily from the accumulation of leaves, twigs, and woody materials with or without a minor component of mosses. The level of decay is the criterion for distinguishing between the L, F and H horizons.
  - L (litter) horizon is characterized by an accumulation of organic matter in which the original structures are easily discernible.
  - F (fermentation) horizon consists of an accumulation of partly decomposed organic matter where some of the original structures are difficult to recognize.
  - H (**humus**) horizon is characterized by an accumulation of decomposed organic matter in which the original structures are indiscernible. This horizon differs from the F by having greater

humification due chiefly to the action of organisms. It is frequently intermixed with mineral grains, especially near the junction with a mineral horizon.

- Of, Om, Oh horizons: wetland soils, peat material (see Figure 13 a)
  In poorly drained soils (wet areas) the organic horizons develop mainly from mosses, rushes and woody materials. Organic matter can develop into thick horizons because of slow decomposition due to water saturated conditions. As with the L, F, H horizons the level of decay is the criterion for distinguishing between the Of, Oh and Om horizons.

  - Of horizon consists largely of fibric materials that are readily identifiable as to botanical origin.
  - Om horizon consists of mesic material partly decomposed both physically and biochemically.
  - Oh horizon consists of humic material, which is at an advanced stage of decomposition. Oh horizons are very stable and change little physically or chemically with time unless they are drained.

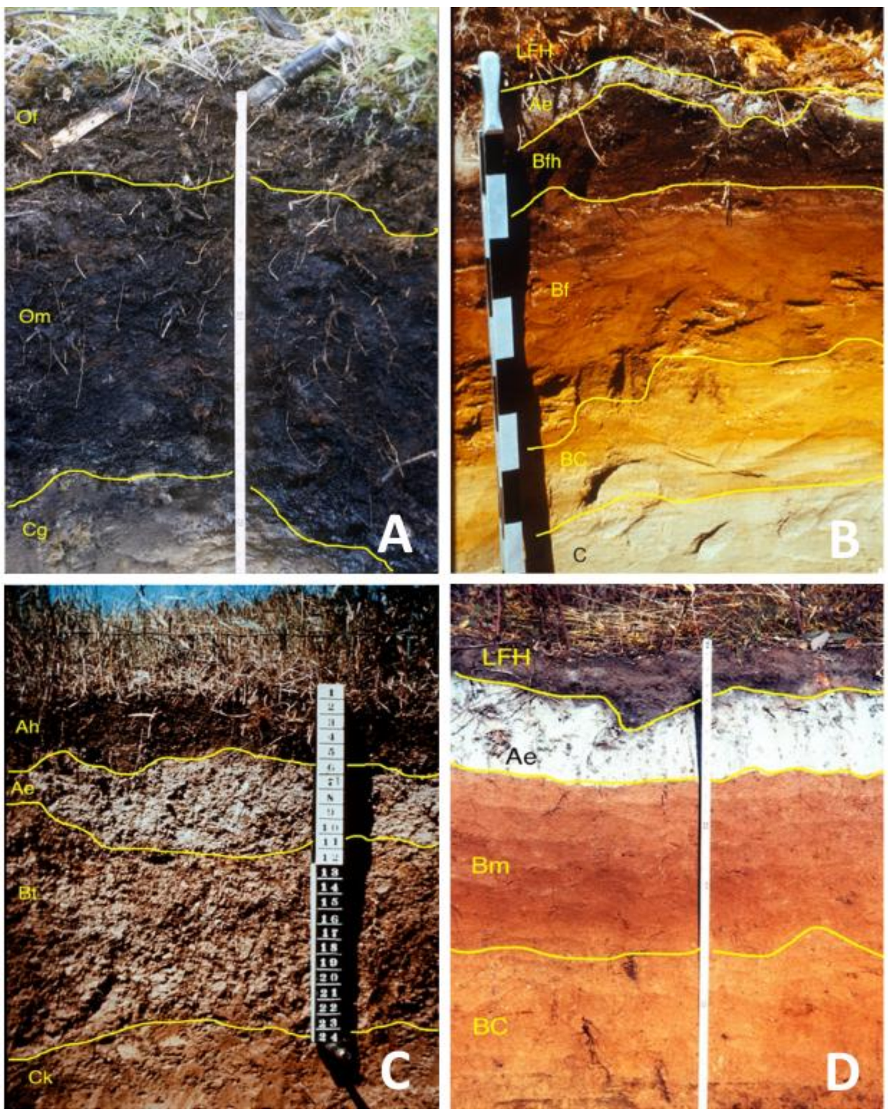


Figure 13: Soil profiles with examples of organic and mineral soil horizons. (Canadian Society of Soil Science, 2020) https://soilsofcanada.ca/imagery-collection/

Figure 14: Soil profiles with examples of organic and mineral soil horizons. (adapted from Hazlett et al., 2020) https://www.mdpi.com/2571-8789/4/3/54

Organic horizons usually exist in soils that are permanently covered by vegetation. Not all soils have organic horizons, and the entire sequence of organic horizons (either L, F, H or Of, Om, Oh) do not need to be present at any specific location. In some cases, soil biological activity is so rapid that organic matter and nutrients are recycled rapidly into the mineral organic horizons. For example, at an upland site with rapid decomposition there may only be an L horizon present. Some species of invasive earthworms that are used for fishing bait, so called "jumping worms", are so voracious that they digest the incoming litter quickly and no organic horizons are able to develop. During a forest fire L, F, H horizons can be lost from a site by combustion leaving mineral horizons at the soil surface.

3.9 Mineral Horizons

Mineral horizons contain 30% or less organic matter.

- A horizon: Surface mineral horizon, usually lies beneath the organic horizons.
    - Ah horizon (h = humus) (see Figure 13 c and 14 b). 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 L, F, H horizons and is therefore dark in colour.
    - Ae horizon (e = eluviation) (see Figure 13 b, d and 14 a). In other soils the A horizon experiences leaching or eluviation of organic matter, iron, aluminum, nutrients and clay as a result of the downward movement of water; this is expressed by a lightening of the soil colour compared to deeper horizons.

  Some profiles have both Ae and Ah horizons. 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.

- B horizon: Subsurface mineral horizon where the materials that are translocated from the upper soil horizons accumulate. This horizon is characterized by enrichment in organic matter, iron and aluminum oxides, or clay; or by the development of soil structure. The B horizon is the zone of accumulation or illuviation.

  - Bh horizon (h = humus). B horizons that have accumulated organic matter as evidenced by dark colors relative to the C horizon.
  - Bf (f = ferric iron) (see Figure 13 b and 14 a, b). Iron and aluminum oxide enrichment in the B horizon exhibits as red, brown and orange colours.
  - Bfh (see Figure 13 b and 14 b). B horizons with both organic matter and iron and aluminum oxide enrichment.
  - Bt (t= translocated clay) (see Figure 13 c). B horizons with clay accumulation as indicated by finer soil textures.
  - Bm (m=modified) (see Figure 13 d). B horizons with only a slight addition of iron, aluminium or clay.

  There is a close relationship between the A and B horizons. Translocations as well as many biological and chemical reactions take place between them.

- C horizon: Also known as the parent material as it is comparatively unaffected by the soil forming processes, particularly weathering, that occurs in the A and B horizons. This horizon can be the transition stage between bedrock and soil or in the case of glaciated landscapes it is the original glacial sediments that were deposited. In very young soils that do not yet have defined horizons, the entire profile of the soil is called the C horizon. There is very little organic material found in this horizon as plant roots do not generally penetrate this deep into the soil.

Any particular soil profile may have only some of the horizons noted. Young soils are shallower and have less differentiated horizons, while the profile of mature soils may display the full set of horizons and more detailed subhorizons.

3.10 Discussion Questions

1. Soils are not rocks, yet the underlying rock has a major influence on soil properties. Why is this?
2. How has current or past human activity influenced the soil forming factors and soil formation? Do you think that it is speeding up or slowing down soil development, causing more or fewer horizons, other effects?

4.0 The Physical Properties of Soils

The physical properties of soils are those that describe the amount, size, shape and arrangement of its particles, and their mineral composition. These properties are also affected by the amount of organic matter in the soil. The physical properties of soil determine if it is strong enough to withstand the weight of traffic or if it will collapse under stress; if a soil can hold large amounts of water for plants to use or if it drains quickly. Agriculture and engineering depend heavily on soil's physical capabilities. Not all soils are appropriate for the same practices and applications, therefore it is important to have a thorough understanding of the physical properties of soils and their impact on soil functions.

4.1 Colour

When we dig a soil pit the first thing we notice is the different colours of horizons. The colour of soil can reveal important details about its properties and the processes operating in the soil profile. Colour variation is a simple and useful way of differentiating soil horizons.

Soil colour is indicative of three important soil conditions: the state of **aeration** and drainage, the organic matter content, and the presence of iron oxidation (see Table 1). Moist soils and those with high organic matter appear darker in colour. Surface horizons rich in organic matter appear darker than subsurface horizons. Red and brown soils are usually well drained and aerated. Also, in well aerated soils, iron is oxidized more readily and develops a 'rusty' colour. Grey and blue soils can indicate an area of poor aeration due to poor drainage, prolonged saturation or waterlogging, especially deeper in the soil profile. The lack of oxygen means that the iron is in its reduced form, which can give soil a grey-blue colour. Grey soils closer to the soil surface can indicate leaching, a process where organic matter, iron and aluminum have been translocated to deeper soil horizons by water percolation.

Table 1: Properties of soil based on colour.

Condition	Dark (black to brown)	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

Soil colour is described in a standardized fashion using notation from the Munsell Soil Colour Charts. The system has three components: **hue** (the colour on the colour wheel), **value** (lightness or darkness), and **chroma** (colour intensity). Higher numbers for value indicate lighter colours and higher numbers for chroma indicate stronger or more highly saturate colours (see Figure 15).

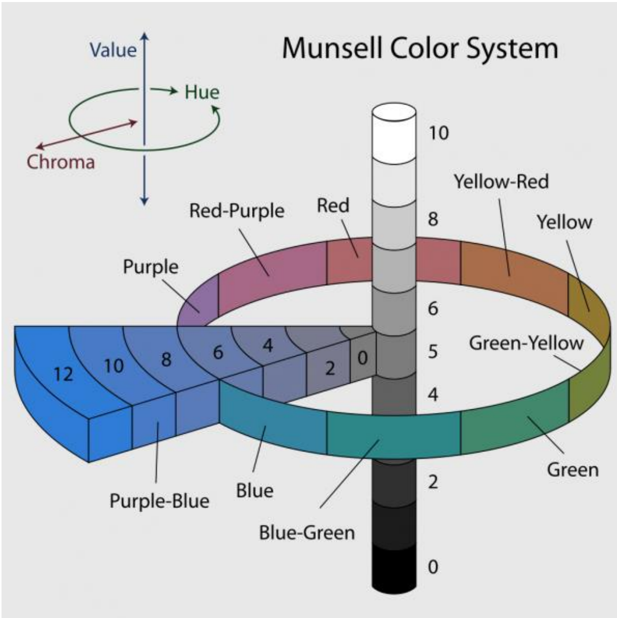


Figure 15: The Munsell colour system.
(https://commons.wikimedia.org/wiki/File:Munsell-system.svg)

The soil sample is compared to the colour chips in the Munsell Soil Colour Book to find a visual match and assigned the corresponding Munsell notation. The notation is written as Hue Value/Chroma. An example would be 2.5YR 4/4. 2.5YR refers to the colour in the yellow-red hue, 4/ refers to the value, and /4 indicates the chroma (see Figure 16).

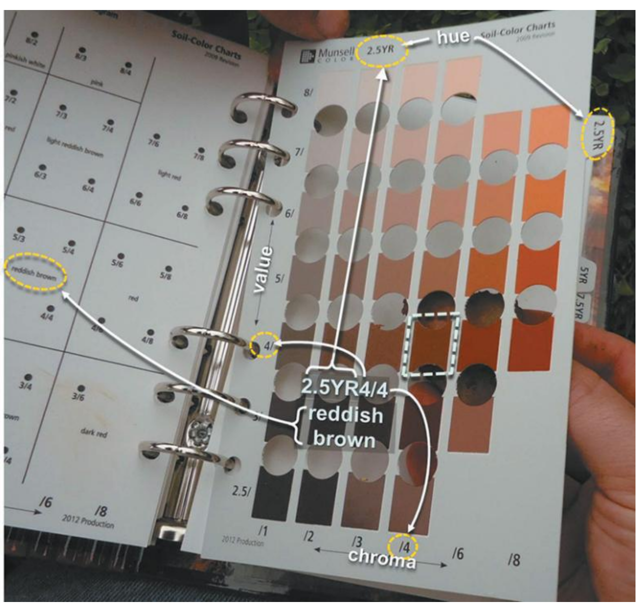
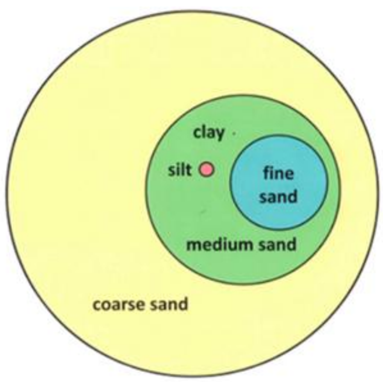


Figure 16: Page from the Munsell Soil Colour Book. The color name "reddish brown" is applied to a group of four color chips as shown on the facing page. (Weil and Brady, 2017)

4.2 Texture

The size and abundance of mineral material in soil is extremely variable and contributes greatly to the properties of each soil. Mineral particles, divided by size, are categorized as **boulder**, **stone**, **cobble**, **gravel**, sand, silt, and clay. Boulders, stones, cobbles and gravel are classified as course fragments and are greater than 2 mm in diameter.

The soil or 'fine earth' includes particles less than 2 mm in diameter (see Figure 17). 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.



Class name	Diameter (mm)
very coarse sand	2.0 -1.0
coarse sand	1.0 – 0.5
medium sand	0.5 – 0.25
fine sand	0.25 – 0.10
very fine sand	0.10 – 0.05
silt	0.05 – 0.002
clay	< 0.002

Figure 17: Comparative size of sands, silt and clay. If clay was the size of a dot on the page, silt and sands would be a comparative size. (adapted from Colorado State University, 2022) https://cmg.extension.colostate.edu/Gardennotes/214.pdf

- Sands range in size from 0.05 to 2 mm in diameter, are easily seen by the naked eye, and give soil a loose, gritty texture. Soils that are dominated by sand generally have large macropores and therefore drain faster than soils which are dominated by clay. Sandy soils also have low nutrient levels limiting plant growth.
- Silt particles are 0.002-0.05 mm in diameter and feel powdery when dry, and smooth but not sticky when wet.
- Clays are the smallest particles, less than 0.002 mm in diameter and are only seen with the aid of an electron microscope. Clay soils are very sticky when wet, and form hard aggregates when dry. Due to their large surface area and charge-carrying **colloids**, clays contribute significantly to the chemical properties of soils. Clay particles have a high attraction for water and nutrients holding them in the rooting zone of plants. Clay soils are more fertile than sandy soils.

Table 2: Influence of soil particle size on soil properties and behaviour.

Property/behaviour	Sand	Silt	Clay
Water-holding capacity	Low	Medium to high	High
Drainage rate	High	Medium	Poor
Suitability tillage after rain	Good	Medium	Poor
Aeration	Good	Medium	Poor
Warm-up in spring	Rapid	Moderate	Slow
Compactability	Low	Medium	High
Soil organic matter level	Low	Medium to high	High to Medium
Decomposition of organic matter	Rapid	Medium	Slow
Ability to store nutrients	Poor	Medium to high	High
Pollutant leaching potential	High	Medium	Low
Sealing of ponds, landfills	Poor	Poor	Good

Based on the percentages of sand, silt and clay, soils are categorized into soil textural classes. The range of each class represent textures with similar properties and are named to identify the dominant particle sizes. Soil texture is the master soil physical property and has a strong influence on other physical, chemical and biological properties of soil. **Permeability**, water retention, aeration, fertility, bulk density, structure, compactability and organic matter decomposition are all affected by the soil texture (see Table 2). **Loams** are a mix of sand, silt and clay. They provide a balance of water holding capacity and nutrient availability between the three particle sizes.

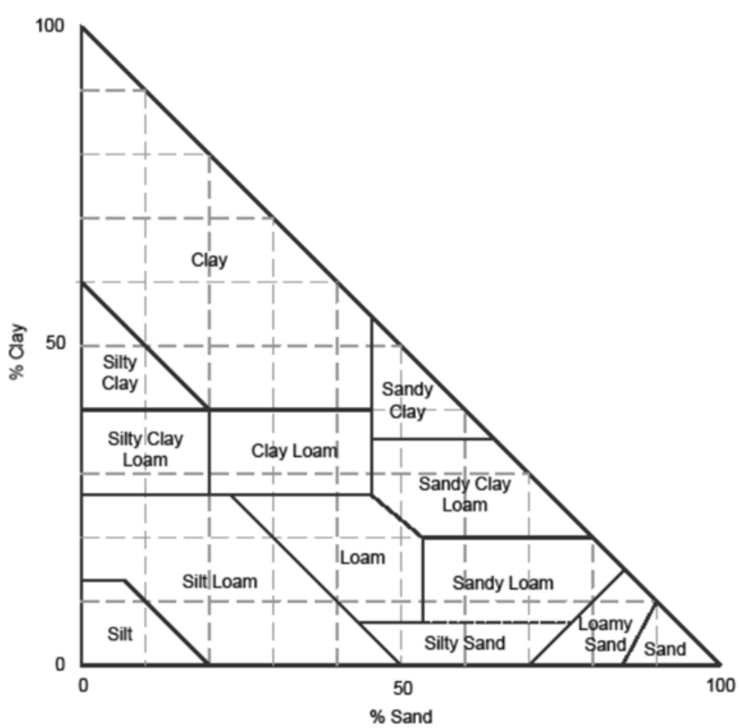


Figure 18: Soil textural triangle. (adapted from Ontario Centre for Soil Resource Evaluation, 1993)

The soil **textural triangle** is used to visually display the different soil textural classes (see Figure 18). The different sides of the triangle represent the percentage of sand and clay sized particles in a sample of soil. The silt percentage for any particular textural class can be calculated by subtracting the sand plus clay percentages from 100%.

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 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.

4.3 Structure

If you look closely at soils, you will notice that sand, silt and clay particles are arranged into larger, secondary 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. The 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, heat transfer 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 reduce the availability of water. Dense or poor structure reduces the movement of air, water, heat, nutrients and **soil biota**.

Physical-chemical (abiotic) and biological (biotic) processes cause the formation of aggregates. Clay particles are attracted to each other to form aggregates in a process called flocculation. Aggregate formation is also enhanced by soil organic matter and soil organisms that produce organic glues that bind soil particles together.

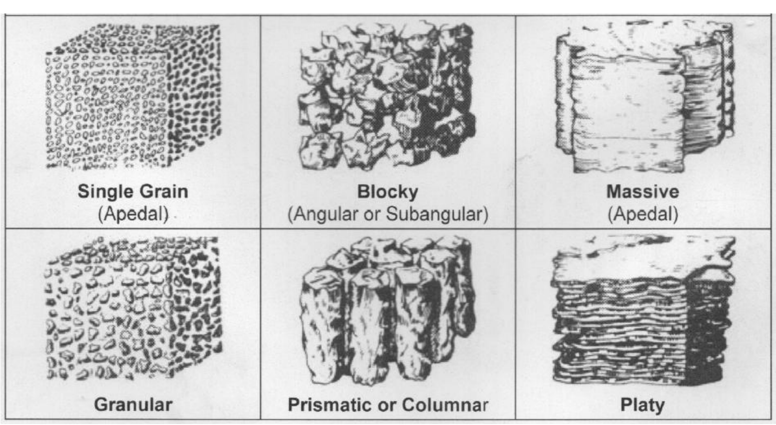


Figure 19: Common kinds of soil aggregation. (Heck et al., 2017)

Aggregates are characterized by their kind (shape) (see Figure 19), class (size) and grade (strength). Sand sized particles do not readily stick together to form stable aggregates and are therefore are structureless, classified as single grain or apedal. You may have noticed this while attempting to build a sandcastle on the beach. Some fine-textured clay soils are also structureless, forming dense and massive chunks that have no visible structure and are hard to break apart.

Other kinds of structure include: granular, blocky, prismatic or columnar and platy.

- Granular structure is 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.
- Blocky structure can be composed of angular block-like or subangular units. This type of structure occurs commonly in soil with high clay content where swelling and shrinking of the clay causes cracks to develop.
- Prismatic or columnar soil structure is formed when freezing/thawing or wetting/drying causes vertical cracks to develop in the soil. Growth of roots on columnar structured soils is rather slow and bound by the density of soil.
- Platy structured soils have flat, thin plates that are oriented horizontally. Platy structures usually hinder downward movement of water and penetration of plant roots through the soil.

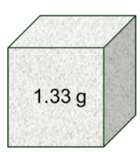
4.4 Bulk Density

Bulk density is a measure of soil compaction and is defined as the dry weight of soil divided by its volume (see Figure 20). This volume includes the volume of soil particles and the volume of pores among soil particles. Bulk density is typically expressed in g/cm3.

Soils that are porous and loose have lower bulk densities than compacted soils. In general, bulk density increases in soils with higher sand content and decreases as organic matter content increases in a soil. 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 decreases in bulk density.

In the field one cubic centimeter (cm^3) of a certain soil appears as….

Solids and pore space



1 cm^3

To calculate bulk density of the soil:

$$\text{Bulk density} = \frac{\text{Weight of oven dry soil (g)}}{\text{Volume of soil (cm}^3\text{) (solids and pore space)}}$$

Weight = 1.33 g (solids only) Volume = 1 cm^3 (solids and pore space)

Therefore:

$$\text{Bulk density, } D_b = \frac{1.33\text{ g}}{1\text{ cm}^3} = 1.33\text{ g cm}^3$$

Figure 20: Example of a bulk density calculation. (adapted from Weil and Brady, 2017)

Bulk density plays an important role in determining if soil has the necessary physical characteristics to support the foundation of buildings, plant growth or water infiltration. Soils with higher bulk densities have lower total pore space than those with lower bulk densities (see Figure 21).

The bulk density of soil is subject to change over time based on the management of the soil. Heavy traffic due to forestry or agricultural equipment asserts high pressure on the soil and can increase the bulk density. Intensive use of soils for hiking and biking trails or campsites can also increase bulk density. With an increase in bulk density, the soil becomes more compact and less pore space is available, this in turn has a negative effect on plant growth and soil organisms. More compact soils inhibit water movement and reduce **infiltration** down the soil profile which can increase runoff and erosion. Soil compaction can be mitigated by spreading the applied weight over a larger area by using machines that have tires with larger surface areas and by scheduling forestry operations on sensitive soils during winter when snow cover protects the soil surface. Applying wood chips or gravel, or building elevated boardwalks are methods that are used to minimize soil compaction on trails.

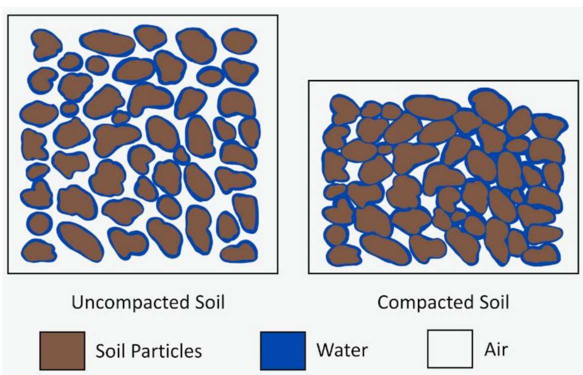


Figure 21: Comparison of uncompacted and compacted soil. (Krzic et al., 2021)
https://openpress.usask.ca/app/uploads/sites/81/2020/08/Ch4_Can-You-Dig-It_compaction-2.png

The most common method of measuring bulk density is the core sample method (see Figure 22). Using this method, a cylinder of known volume (with two open ends) is pushed or hammered into the soil to obtain an undisturbed core sample without compaction. The core can be sampled vertically from the soil surface or horizontally into the profile face of a soil pit. The sample inside the core is trimmed on the ends with a knife to yield a core whose volume can easily be calculated from its length and diameter. The core is extracted and oven dried to remove 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 22: Bulk density sampling with a drop hammer sampler. (Weil and Brady, 2017)

4.5 Pore Space

Pore space is the space occupied by water and air in a soil and is measured as a percent. The percent pore space is also known as total porosity. Pore space is inversely related to bulk density. More compacted soils with higher bulk densities will have less pore space. Surface soil horizons with high organic matter content and good structure can have pore space up to 60%. For compacted subsurface horizons pore space can be as low as 25%.

The size and shape of pores is highly variable (see Figure 23). Macropores (larger than 0.08 mm) are found between aggregates or can occur as the spaces between individual grains in coarse-textured sandy soils. Micropores (smaller than 0.08 mm) occur inside aggregates or between fine-textured clay soils. Water and air move easily through macropores in contrast to micropores where the pore space is usually filled with water, drainage is slow, and there is little air movement. Macropores and micropores also provide space for organisms to live and for plant roots to grow. Macropores called biopores can be created by earthworms and other soil organisms. Other macropores are formed when tree roots die and the outer bark of the root is resistant to decay creating root channels in soil that provide conduits for water, air and new root growth.

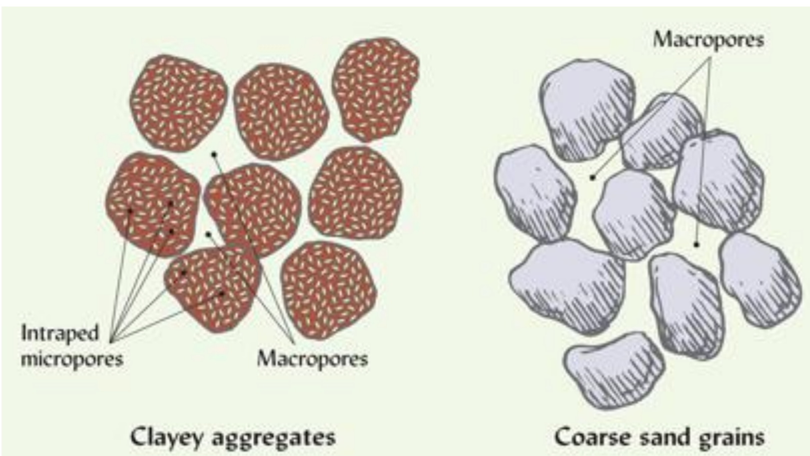


Figure 23: Macropores and micropores (Weil and Brady, 2017)

Similar to bulk density, pore space can be altered by different soil management practices. Breaking down soil aggregates and compacting soil through machinery use and foot traffic will decrease pore space and reduce drainage, restrict air movement and decrease organism activity in soil. A clay soil with good structure (medium aggregate size, abundant pores between and within aggregates) will have macropores that facilitate drainage and aeration and micropores that hold water for plants during dry weather periods.

4.6 Learning Activity

Determination of textural class using the field estimation of textural class method
Textural class can be determined in the field by testing the cohesiveness, stickiness, and feel of a mineral soil sample. The method uses three separate tests that measure the behaviour of a small handful of soil and follows a flow diagram to estimate the soil textural class. (adapted from Heck et al., 2017; Ritchey et al., 2015). https://uknowledge.uky.edu/cgi/viewcontent.cgi?article=1139&context=anr_reports

Activity Description

Preparation of soil for determination of textural class by feel:
Place approximately one golf ball sized volume of soil in the palm of your hand. Slowly wet and knead, removing any particles > 2 mm. Soil is ready when it is plastic but leaves negligible moisture when dabbed on skin.

1. Preliminary moist cast test:
   Compress ball of moist soil by clenching in the palm of your hand. If the soil holds together and withstands handling (lightly squeezing between thumb and forefinger, or transferring back and forth between hands) then it forms a cast and is cohesive.

2. Ribbon/flake test:
   Moist soil is rolled into cylindrical (worm) shape (~ 1 cm diameter). Press the cylinder out between thumb and forefinger forming a ribbon of uniform width and thickness (~ 3 mm). Measure the length of the ribbon that is self-supporting against gravity beyond your forefinger. Silty soil will flake off the thumb, when rubbed against the forefinger.

3. Slurry test:
   A pinch of moist soil is placed into the palm of your hand. Water is added and the sample is rubbed with your finger into a thick slurry. A very abrasive slurry is indicative of sand; very slippery is indicative of silt.

Step 1: Start with a small handful of soil, about the size of a golf ball, and slowly add water a drop at a time, mixing as you go, until you have a ball of soil that has the consistency of putty. Gently squeeze the ball to determine if it will stay together in a ball or fall apart.

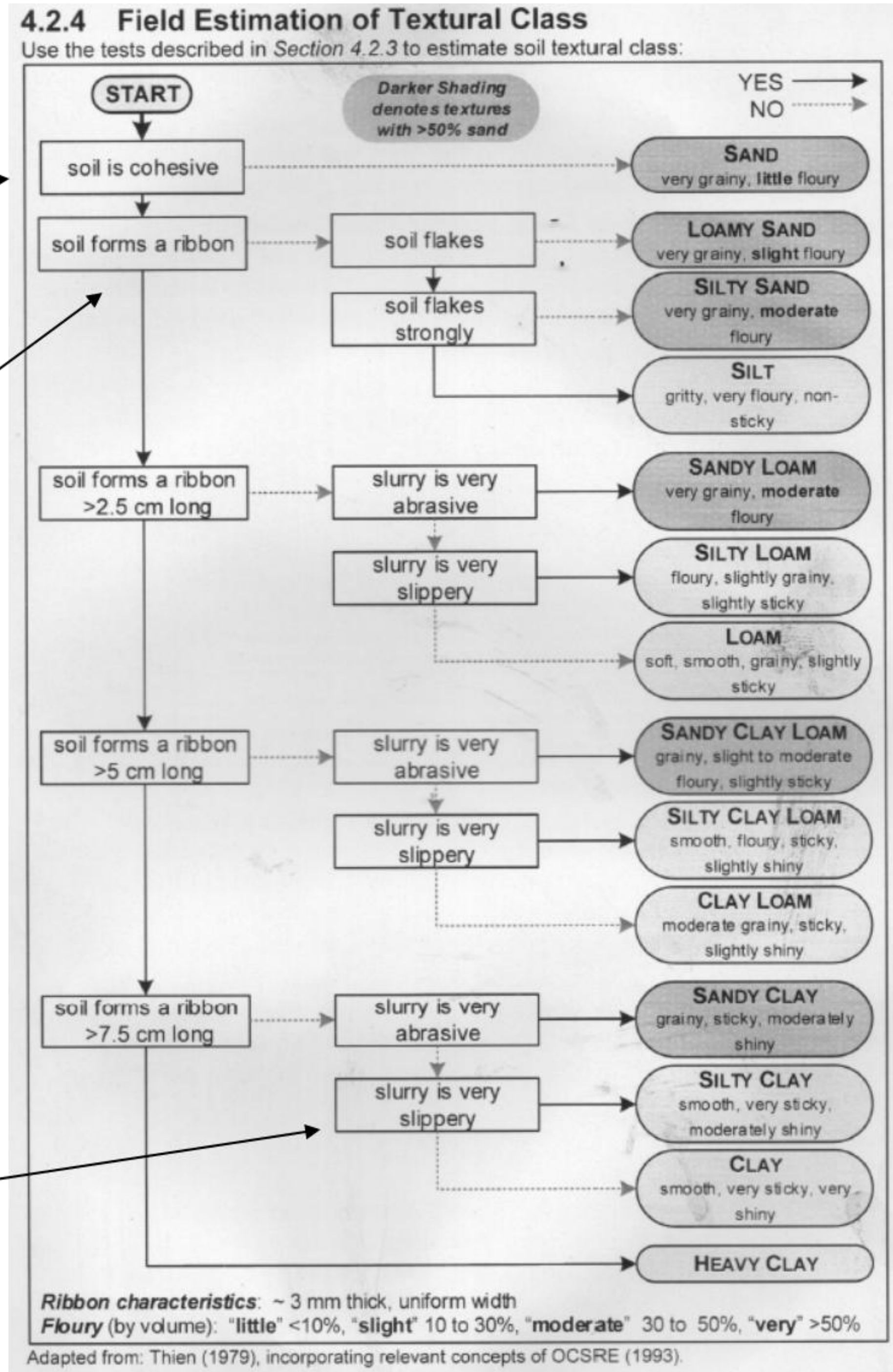
Step 2: If the ball of soil stays intact, gently press the ball between your thumb and index finger, trying to work it out to form a ribbon. If you can form a ribbon, measure how long the ribbon is before it falls apart.

Step 3: After completing the ribbon test, add water to a pinch of soil in the palm of your hand until you have a muddy puddle. Rub the mud puddle against your palm and determine if it feels gritty, smooth, or equally gritty and smooth.

Step 1.
Preliminary Moist Cast Test

Step 2.
Ribbon/Flake Test

Step 3.
Slurry Test

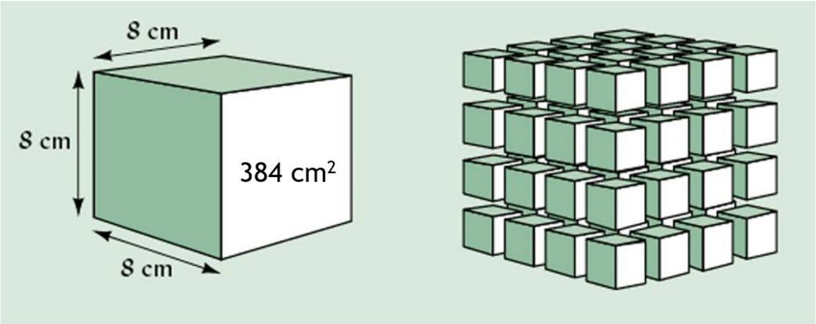


5.0 The Chemical Properties of Soils

The chemical properties of soils are those that describe the concentrations and proportions of dissolved ions in soil water and those held by the soil particles. Soil is made up of inorganic and organic materials, and air and water. Soil is a dynamic system where chemical ions are moving between, and interacting with, these four different components. Soil is the primary source of many nutrients for plants. If soil lacks adequate quantities of nutrients, or if nutrients are locked in an unavailable form in the soil, plants may become unhealthy and die. In addition to a focus on plant growth and crop yield, soil chemistry also examines the fate, transport, and potential toxic impacts of contaminants that have been released into 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.

5.1 Soil Colloids

Soil chemical properties are determined largely by tiny soil particles called soil colloids. Soil colloids are clay and organic matter (humus) particles smaller than 0.001 mm in diameter. The importance of colloids relates to their large surface area per unit mass. Other soil particles also have a surface area, but the surface area of colloids is more than 1000 times the surface area of the same mass of sand particles (see Figure 24). The surface area of colloids carry predominately negative electrostatic charges and soil chemical properties are controlled by reactions between the colloid surfaces and **soil solution**. The surface of colloids attracts soil nutrients but also releases them to plants which take them up through their root systems. Without colloids holding on to these nutrients they would percolate away in soil water to ground and surface water. Soil colloids also bind with heavy metals, water molecules, pesticides and herbicides and other organic and mineral substances.



6 sides X 64 cm^2 = 384 cm^2 64 cubes X 6 sides X 4 cm^2 = 1536 cm^2

Figure 24: Relationship of surface area and particle size. For the single cube on the left the surface area is 384 cm^2. If this cube were cut into 64 smaller cubes the same mass would have a surface area of 1536 cm^2. (adapted from Brady and Weil, 2017)

5.2 Cation Exchange Capacity

One of the most important roles of soil colloids is the ability of their negative charges to attract positively charged ions (cations). The cations in soil are primarily derived from physical and chemical weathering. The six most abundant exchangeable cations in the soil are:

Base cations:
calcium (Ca^{2+})
magnesium (Mg^{2+})
potassium (K^{+})
sodium (Na^{+})

Acid cations:
aluminum (Al^{3+})
hydrogen (H^{+})

Cations that are held close to the soil colloids are said to be adsorbed inside the **soil exchange complex**. **Cation exchange capacity** (CEC) refers to a soil's ability to maintain reserves of cations. CEC is defined as the total amount of exchangeable cations a particular soil can hold expressed as a measurement of charge in **centimoles** of positive charge per kg of oven dry soil (cmol (+) kg^{-1}). CEC is an important property of soil because it is a useful indicator of soil fertility, nutrient retention capacity, and the capacity to protect **groundwater** from contamination.

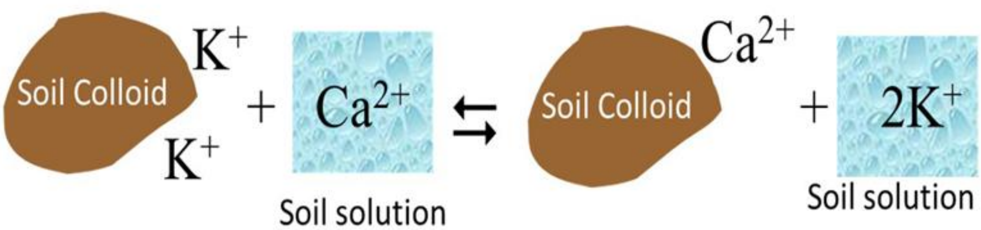


Figure 25: Cation exchange between the exchange complex and soil solution. (Krzic et al., 2021)
https://openpress.usask.ca/app/uploads/sites/81/2020/10/5-07.png

Other cations in soil are found further from the surface of soil colloids, free floating in the soil solution. The interchange between a cation in soil solution and another cation on the surface of a negatively charged colloid (clay or organic matter) is called cation exchange (see Figure 25). The cation exchange process is reversible and occurs on a charge for charge basis, meaning a Ca^{2+} ion in soil solution exchanges with two K^{+} exchangeable ions held in the soil exchange complex as shown in Figure 6.2. Once cations are exchanged and released into the soil solution, they can be taken up by roots and soil organisms. In one example of cation exchange plant root hairs exude H^{+} ions into soil solution which exchange with nutrient cations from the exchange complex. The nutrient cations exchanged into soil solution can then be taken up by plants or soil organisms, or leached away in drainage water.

Since the number of colloids increases in soils with higher clay contents, CEC is dependent on soil texture. The range of estimated CEC for different soil textural classes is shown below (values in cmol (+) kg^{-1}).

- Sand = 0-3
- Loamy Sand to Sandy Loam = 3-10
- Loam = 10 - 15
- Clay Loam = 10-30
- Clay = > 30

Other factors that influence CEC are the soil organic matter content (more organic matter increases colloids in soil), the type of clay (clays come in a range of structures and some clays have greater surface areas than other clays), and soil pH (as pH increases the number of negative charges on colloids increase).

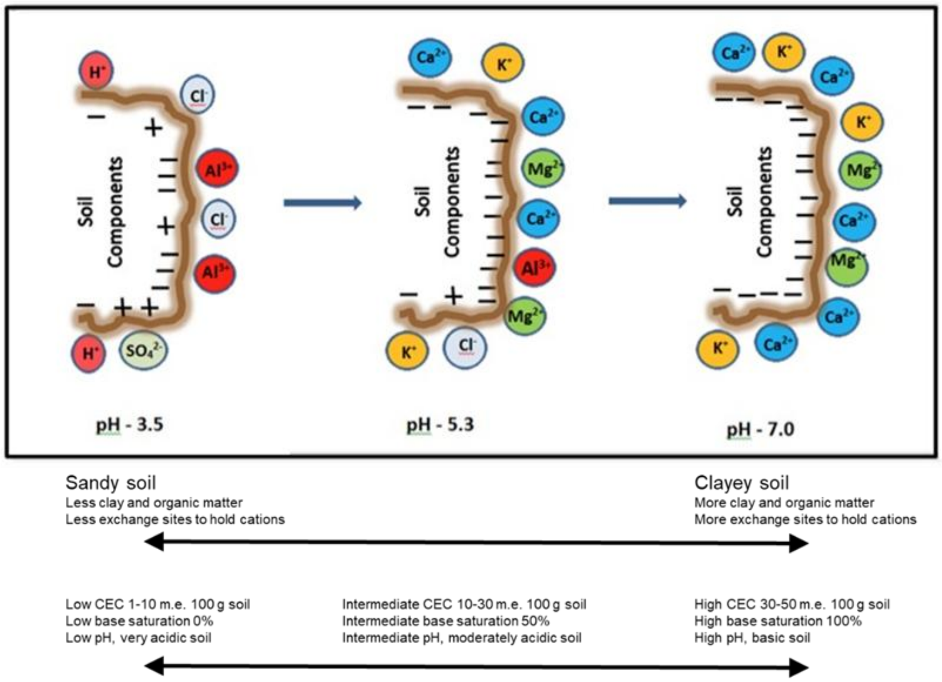


Figure 26: Relationship of cation exchange capacity with texture, pH and base saturation. (adapted from University of Georgia Extension, 2022)
https://extension.uga.edu/publications/detail.html?number=C1040&title=cation-exchange-capacity-and-base-saturation

The cations that dominate the exchange complex have a marked influence on soil properties. In a given soil, the proportion of the CEC occupied by the base cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) is termed the base saturation percentage. Base saturation is positively related to soil pH. Acidic soils with low pHs will have low base saturation percentage, whereas soils with higher pHs will have high base saturation percentages. Soils with high CEC, high base saturation percentage and high pH are more fertile than soils with low CEC, low base saturation percentage and low pH (see Figure 26). A soil with low CEC is unable to hold nutrients that are applied through fertilization and therefore has limited availability of nutrients to plants and microorganisms. Addition of organic matter to soil is a management practice that can be used to assist in raising the CEC and overall fertility of the soil.

5.3 pH – Acidity and Alkalinity

Soil **pH** describes the **acidity** or **alkalinity** of the soil and is a measure of the concentration of hydrogen (H^+) ions in soil solution that is expressed as a negative logarithm ($pH = -\log[H^+]$). The pH scale runs from 0-14, where a pH of 7 represents an equal concentration of acids and bases and is called neutral (see Figure 27). pH readings below 7 are considered acidic and any pH above 7 is called alkaline. As the concentration of H^+ ions increases (i.e. solution becomes more acidic) the pH decreases. High pH values indicate low acidity. The pH scale is logarithmic, which means that for every one-unit change in pH there is a 10-fold change in the concentration of H^+ ions in the soil solution. For example, a soil with pH 4 has one thousand times (10 X 10 X 10 = 1000) more H^+ ions in solution than a soil with pH 7. This means a pH 4 soil is one thousand times more acidic than a pH 7 soil.

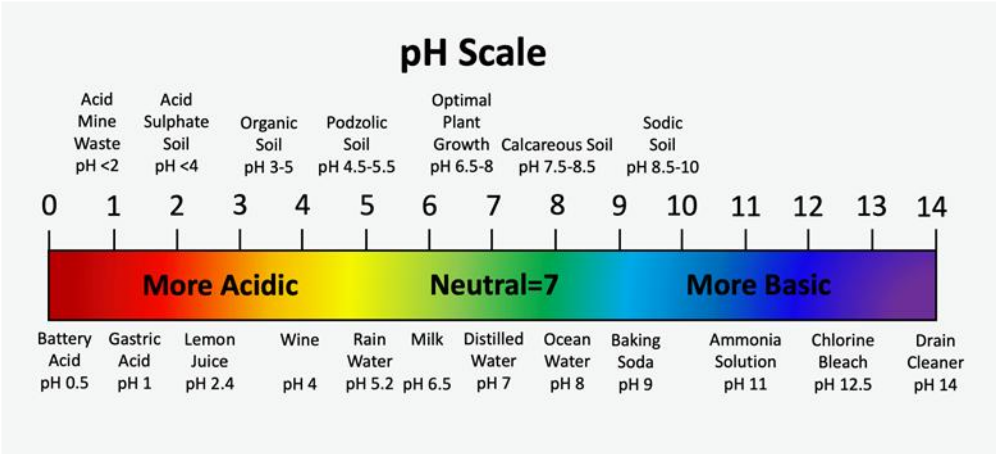


Figure 27: The pH scale with some common materials and soils. (Krzic et al., 2021)
https://openpress.usask.ca/app/uploads/sites/81/2020/08/soil-pH-big-image.png

Soil pH is the master soil chemical property that affects a wide range of soil properties. Soil pH controls:

- plant nutrient availability
- mobility of pollutants
- weathering of primary minerals
- abundance and kinds of soil organisms which controls the decomposition of organic matter in soil
- aggregate stability (at low pH fungi dominate and stabilize aggregates together through hyphae) which affects pore space, infiltration and aeration
- plant distribution

One of the most significant influences exerted by pH is the solubility and plant availability of essential nutrients. Considering all the plant nutrients in Figure 27 the ideal pH for nutrient availability is a range between 6.0 and 7.5. Below a pH of 6.0, nitrogen, phosphorus, and potassium become less available, and as the pH approaches 5.5 iron, manganese, copper and zinc become soluble and available for uptake by plants in excessive quantities that can be 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 pHs above 7.5, some essential nutrients are less available and symptoms of deficiency may result.

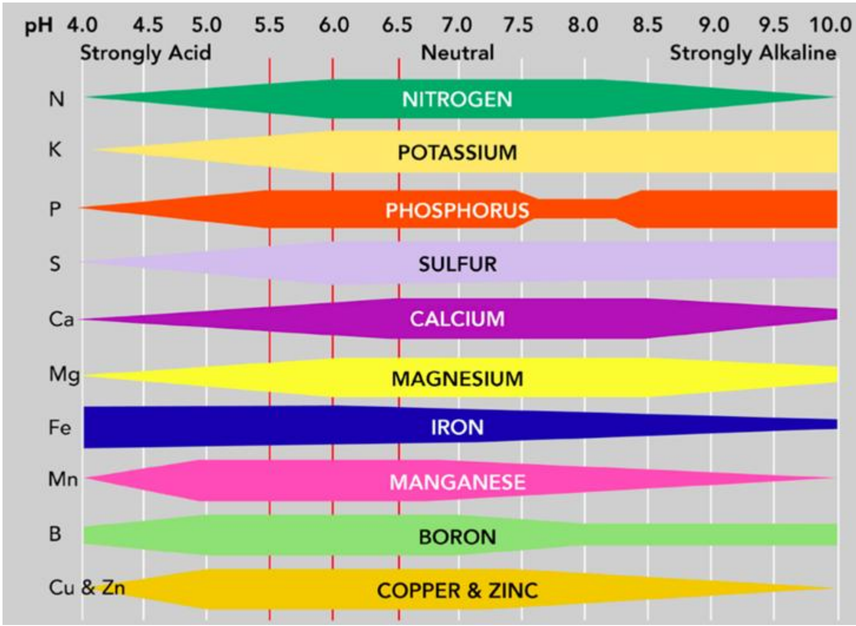


Figure 28: Soil pH and plant nutrient availability. A wider bar indicates higher availability of the nutrient. (adapted from RX Green Technologies, n.d.) https://www.rxgreentechnologies.com/wp-content/uploads/2020/02/Plant-Substrate_Interaction-1.pdf

It is important to recognize that when plants are showing a nutrient deficiency it may not be from low levels of that specific nutrient in the soil. When soil pH is outside the optimum range for any specific nutrient it means that nutrient is held in the soil in a form that is unavailable to the plant. Adding additional nutrients to the soil will not correct the deficiency. Excessive acidity or alkalinity which may cause low plant nutrient availability can be corrected. Soil pH can be increased through the application of liming materials such as ground limestone or industrial by-products that contain calcium oxides or hydroxides such as wood ash. Lowering of soil pH due to high alkalinity can be achieved by incorporating elemental sulfur into the soil.

Table 3: Optimum soil pH for common Ontario trees and plants.

Species	Optimum soil pH
Walnut	6.0-8.0
Sugar Maple	6.0-7.5
Ash	6.0-7.5
Oak	5.0-6.5
Tamarack	5.0-6.5
Balsam Fir	5.0-6.0
White Spruce	5.0-6.0
Red Pine	5.0-6.0
White Pine	4.5-6.0
Black Spruce	4.0-5.0
Blueberry	4.0-5.0
Cranberry	4.2-5.0
Sphagnum Moss	3.5-5.0

All plants and soil organisms exhibit different preferences and tolerance for acidity and alkalinity in their environment (see Table 3). Ideal conditions, or the optimum pH range, can vary widely from one organism to another. Specific levels of soil pH are needed to grow, thrive, and fight off disease. Understanding which plants can thrive in the soil at a particular location is key to reforestation, agriculture and land restoration. Table 3 gives a list of some common Ontario trees and plants and their pH tolerance levels.

5.4 Soil Fertility and Essential Nutrients

Soil fertility is defined as the ability of soil to supply nutrients to plants in optimal quantities to promote growth. Each soil has a natural fertility that depends on the soil forming factors; climate, organisms, relief, parent material and time. The natural soil fertility of any given site provides a good indication of what plant species will grow there, without human intervention.

An essential nutrient is an element that is necessary for plant growth and reproduction. There are 17 essential plant nutrients. Carbon (C), hydrogen (H) and oxygen (O) are derived from air (carbon dioxide) and water and are required in the plant processes of photosynthesis and respiration. These three elements are used by plants to make up most of their biomass, approximately 95% by weight. The remaining 14 elements are derived from the soil, absorbed primarily as ions carried in soil solution, drawn into soil roots (see Table 4).

There are two main groups of soil nutrients, each distinguished based on the quantity of the nutrient that is required for healthy plant growth. Macronutrients are those nutrients that are required in relatively large quantities whereas micronutrients are required in comparatively small quantities. Macronutrients are also present in higher concentrations in plant biomass than micronutrients.

Table 4: Soil macronutrients and micronutrients and their role in plants. (adapted from Michigan State University, 2013)
https://www.canr.msu.edu/news/knowing_nutrient_mobility_is_helpful_in_diagnosing_plant_nutrient_deficienc

Element	Symbol	Role in Plants
Macronutrients		
Nitrogen	N	Formation of amino acids, vitamins and proteins; cell division
Phosphorus	P	Energy storage and transfer; cell growth; root and seed formation and growth; winter hardiness; water use
Potassium	K	Carbohydrate metabolism, breakdown and translocation; water efficiency; fruit formation; winter hardiness; disease resistance
Calcium	Ca	Cell division and formation; nitrogen metabolism; translocation; fruit set
Magnesium	Mg	Chlorophyll production; phosphorus mobility; iron utilization; fruit maturation
Sulfur	S	Amino acids formation; enzyme and vitamin development; seed production; chlorophyll formation
Micronutrients		
Boron	B	Pollen grain germination and tube growth; seed and cell wall formation; maturity promotion; sugar translocation
Chlorine	Cl	Role not well understood
Copper	Cu	Metabolic catalyst; functions in photosynthesis and reproduction; increases sugar; intensifies color; improves flavor
Iron	Fe	Chlorophyll formation; oxygen carrier; cell division and growth
Manganese	Mn	Involved in enzyme systems; aids chlorophyll synthesis; P and Ca availability
Molybdenum	Mo	Nitrate reductase formation; converts inorganic phosphates to organic

Nickel	Ni	Nitrogen metabolism and fixation; disease tolerance
Zinc	Zn	Hormone and enzyme systems; chlorophyll production; carbohydrate, starch and seed formation

Growth and development become limited by the least available plant nutrient, regardless of how much of the other nutrients are available to the plant. When one or more nutrients limit the plant's ability to grow and reproduce, we say that the plant is deficient in that particular nutrient(s). Deficiencies cause symptoms in plants, which are visual signs or conditions that result from a deficiency. Symptoms such as discolouration or deformations of plant structures as well as declines in plant growth can aid in diagnosing a nutrient deficiency. Measuring nutrient levels in soil and plant tissue can confirm specific nutrient deficiencies. Experimental work has developed optimum soil and tissue concentrations and soil and tissue testing results come with diagnosis of nutrient deficiencies and recommendations for correcting these deficiencies.

Nutrient deficiencies can occur when nutrients are removed from an ecosystem at a rate that is greater than their replenishment. Erosion, leaching and harvesting of plants are examples of nutrient loss processes. Soils that are deficient in one or more nutrients can be replenished by human intervention to maintain long-term fertility and plant productivity. This can be done through the addition of organic soil amendments, nutrient fertilizers or through soil conservation practices that recycle ecosystem nutrients.

5.5 Nutrient Cycling

Nutrient cycling describes the use, movement and recycling of nutrients in the environment. All nutrients are part of a cycle that includes living and nonliving components and involves geological, biological and chemical processes. Soil is at the centre of the nutrient cycles that transform, transport and recycle nutrients that are essential for plant growth.

A core component of all nutrient cycles is the uptake of nutrients by plants and animals and the release of these nutrients back into the soil after death and decomposition. The decomposition process is facilitated by soil organisms that breakdown the organic materials and transform the nutrients. As a nutrient cycles through the soil it will occur in various chemical forms, each with different properties that determine its behaviour in the ecosystem.

Nutrient cycles do not only affect soil fertility and the biosphere. The health of the hydrosphere, atmosphere and lithosphere are also influenced by the range of nutrient cycle processes. A sustainable ecosystem is one where nutrients are recycled endlessly without depleting the overall nutrient supply or disrupting other earth subsystems. In some cases, human intervention can lead to disturbance of a nutrient cycle leading to decreased soil fertility and plant productivity or other ecosystem impacts.

An example of this in forestry relates to the practice of full-tree harvesting, where the entire tree, including branches and foliage (also known as slash) are removed from a logged site. The slash contains valuable nutrients that if left on site, decompose, recycling the nutrients back into the soil. Through an assessment of the natural soil fertility of a given site and the possible forestry harvesting practices that could be utilized, forest managers must ensure that they are not disrupting the nutrient cycle to such a degree that there is a decrease in site productivity. For some sites the decision could be made to not permit full-tree harvesting. Another example of human disruption of nutrient cycling has occurred with the deterioration of water quality caused by the over application of fertilizers. Excessive algae growth or eutrophication of surface waters has resulted due to an increase in phosphorous and nitrogen from agricultural runoff. Limiting fertilizer use or planting trees in riparian areas along the shores of rivers and lakes to take up nutrient runoff are possible ways to solve this problem.

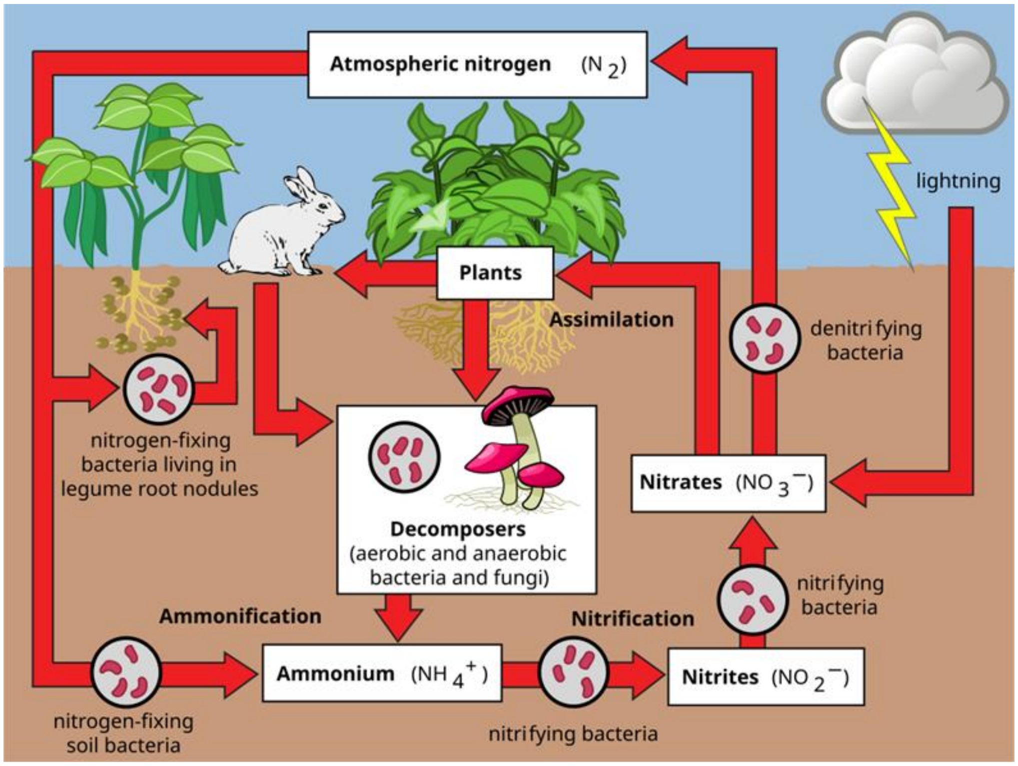


Figure 29: The nitrogen cycle. (Wikipedia, 2019)
https://en.wikipedia.org/wiki/Nitrogen_cycle#/media/File:Nitrogen_Cycle_2.svg

As an example of a nutrient cycle, the steps of the nitrogen cycle are described below and shown in Figure 29. Nitrogen is a major part of proteins, enzymes, nucleic acids and chlorophyll. These compounds control nearly all plant biological processes.

1. Although air is 79% nitrogen gas (N_2), most living organisms cannot use nitrogen in this form. Nitrogen-fixing bacteria play a crucial role in fixing atmospheric nitrogen into nitrogen compounds that can be used by plants.
2. Ammonium nitrogen (NH_4) is subsequently converted to nitrite (NO_2) and nitrate (NO_3) by bacteria known as nitrifying bacteria.
3. Plants absorb the usable nitrogen compounds from the soil through their roots. These nitrogen compounds are used for the production of proteins and other compounds in the plant cell.
4. Animals (including humans) assimilate nitrogen by consuming plants or other animals that contain nitrogen.
5. **Decomposers** recycle dead organic plant and animal matter to soil where bacteria convert these organic nitrogen compounds into NH_4.
6. Depending on site conditions denitrifying bacteria can also convert NO_2 and NO_3 to N_2, releasing it back into the atmosphere.
7. These sets of processes repeat continuously to recycle nitrogen maintaining soil fertility and the percentage of nitrogen in the atmosphere.

5.6 Learning Activity

Chemical Tests for Soil

Knowledge of the chemical properties of soil is essential to understanding plant growth. Soils can be tested for pH and essential plant nutrients using field test kits (i.e. colorimetric determinations) or classroom laboratory methods (e.g. pH meters). Classroom nutrient soil testing kits are available for sale from education supply companies such as Spectrum and LaMotte.

Activity Description

1. Collect soil samples from different locations and different horizons.
2. Gently crush soil to break up soil aggregates.
3. Remove coarse fragments by hand removal or sieving through a 2 mm screen.
4. Follow instructions for pH and nutrient determinations.
5. Record data and compare the results between samples.

6.0 The Biological Properties of Soils

The biological properties of soils refer to the living organisms found in soil and the direct and indirect influence of these organisms on soil characteristics and processes. Soil biological properties reflect how well-suited a soil is to support life. Soil organisms include both fauna (animals) and flora (plants and non-animal microorganisms). The interactions between, 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 attributed to the fact that the 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.

6.1 Soil is Life

Although not generally visible to the naked eye, soil is one of the most diverse and complex ecosystems (see Figure 30). Nowhere in nature are species so densely packed as in soil communities. Soil biota are organisms that spend all or a portion of their lifecycle within the soil or on its immediate surface. Soil biodiversity is defined as the variety of life found in soil, it includes numerous species of invertebrates and microorganisms, soil flora, plant roots, mammals, birds, reptiles and amphibians. Most of the organisms inhabiting soil ecosystems are found within the top 10 cm of the soil profile. Many of the soil organisms live in the pore space between solid mineral and organic particles.

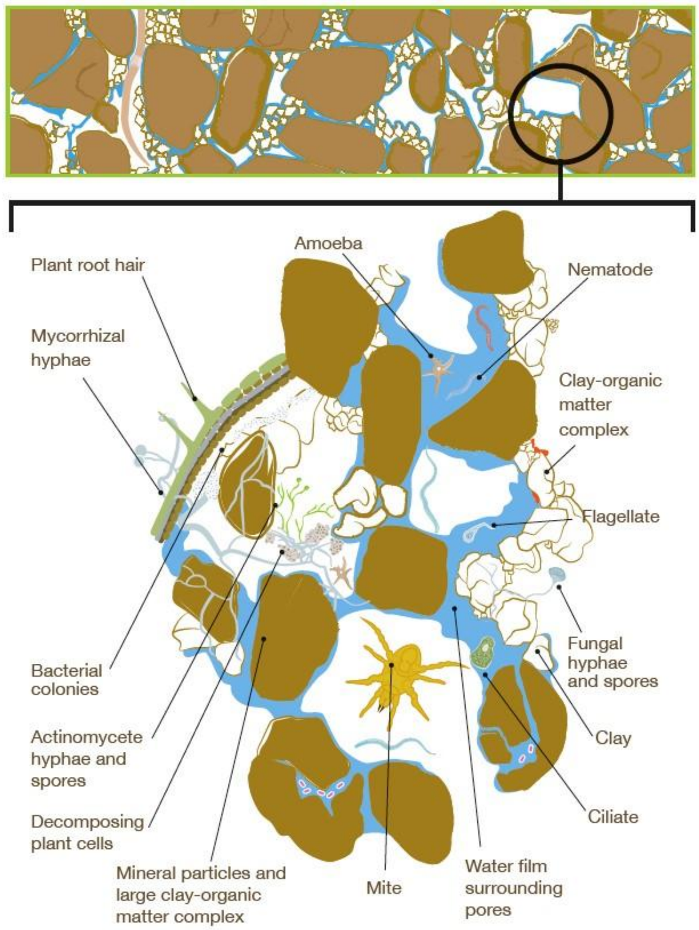


Figure 30: Horizontal cross-section of a highly structured biologically active soil. (Agriculture and Horticulture Development Board, 2024)
https://ahdb.org.uk/knowledge-library/soil-organisms-stabilise-soil-structure

Soil communities are very diverse in size and number of species, which are defined by the chemical and physical nature of the soil body. Soil texture and structure, abiotic conditions (sunlight, rainfall, wind) and interactions with other organisms are factors that determine the level of soil biodiversity. The amount of organic matter found in soil has a large impact on the surrounding biodiversity as it influences soil fertility and structure, workability and water-holding capacity. Soils with good structure have increased water-holding capacity, which promotes root growth, maintains aeration and drainage, and provides habitat for organisms. It is often said that a handful of soil has more living organisms than there are people on planet Earth.

6.2 Who Are These Critters?

The incredible diversity of life that inhabit soil, range in size from single-cellular submicroscopic organisms such as bacteria to larger more complex organisms such as moles and snakes. Soil organisms are categorized in terms of size and include, macrobiota, mesobiota and microbiota (see Table 5).

- Macrobiota refers to organisms that are visible to the naked eye. These organisms dig into the soil for shelter and feed on, or in, the soil. Macrobiota include vertebrates such as moles, and groundhogs and invertebrates such as ants, termites and earthworms.

- Mesobiota are 0.1-2 mm in diameter and generally live within soil pores. These organisms, such as springtails, have little ability to burrow and generally feed on organic material and other soil organisms to survive.
- Microfauna are the smallest organisms and generally live in the soil water films. Examples of microfauna include nematodes and tardigrades.
- Microflora which are comprised mostly of bacteria, fungi and are extremely abundant and diverse and are able to decompose residual organic matter.

Table 5: Important groups of soil organisms by size class. (adapted from Weil and Brady, 2017)

Grouping by body width in mm	Taxonomic Groups	Examples
Macrobiota (> 2 mm)	Vertebrates	Groundhogs, moles, snakes, salamanders
	Arthropods	Ants, termites, millipedes, centipedes
	Annelids	Earthworms
	Mollusks	Snails, slugs
Mesobiota (0.1-2 mm)	Arthropods	Mites, collembola (springtails)
Microbiota (< 0.1 mm)		
Microfauna	Nematoda	Nematodes
	Rotifera	Rotifers
	Tardigrades	Water bears
	Protozoa	Amoebae, ciliates, flagellates
Microflora	Vascular plants	Root hairs
	Algae	Greens, yellow greens, diatoms
	Fungi	Yeasts, molds, mushrooms
	Bacteria	Acidobacteria, blue-green algae

6.3 Functions of Soil Organisms

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. 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 impacts soil quality and functions by providing essential services to the abiotic components of the soil (see Table 6). Due to the extensive functions of soil organisms, declining soil biodiversity will have dramatic negative impacts on ecosystem processes and ecosystem stability.

Table 6: Soil organism ecosystem functions.

Organism Function	Comments
Decomposition of organic matter	The most obvious function carried out by soil organisms. Up to 80% of the organic material fixed by primary producers flows to the **detrital** food chain.
Nutrient cycling	As organic matter is processed, nutrients are released into the environment and become available for recycling back to primary producers. Soils are the stomach of the earth, consuming, digesting, and cycling nutrients and organisms.
Carbon sequestration	Organic residues from decomposition become part of the stable structural **carbon pools** of terrestrial ecosystems.
Production and consumption of trace gases	As soil organisms decompose 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.
Soil detoxification	Soil organisms process (degrade, produce, alter) a variety of water, soil and air pollutants of human origin, including pesticides, trace metals and industrial compounds.
Suppression of pests, parasites and diseases	Soil organisms are natural enemies of some insect pests and diseases. The use of natural enemies to manage pests and diseases is called biological control.
Sources of medicines	Many of our medicines are derived from chemicals excreted by soil microorganisms to defend themselves. Soil bacteria make many of the familiar antibiotic medicines we use (penicillin, erythromycin, streptomycin, tetracycline).
Plant growth control	Soil organisms form symbiotic relationships with plants and their roots. **Mycorrhizae** fungi assist plants in acquiring nutrients and water. The fungus gets sugars from plant photosynthesis. Rhizobium bacteria thrive on the surface of roots of specific legumes and benefit from the supply of proteins and sugars. The bacteria 'fix' nitrogen gas in the air into plant-available forms of nitrogen.
Development and maintenance of soil structure	Soil organisms help to produce and maintain the physical structure of soil. 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. Soil structure regulates water and air movement and gas exchange through the soil profile.

6.4 The Soil Food Web

Soil is a complex ecosystem with a community of diverse organisms that occupy a broad range of niches. Soil organisms are intimately related and interact through a complex network of energy and nutrient transfers known as the soil food web. The steps in energy transfer (feeding of one organism on another) are referred to as trophic interactions. The soil food web is the community of organisms that spend all, or a portion, of their lives in or around the soil (see Figure 31).

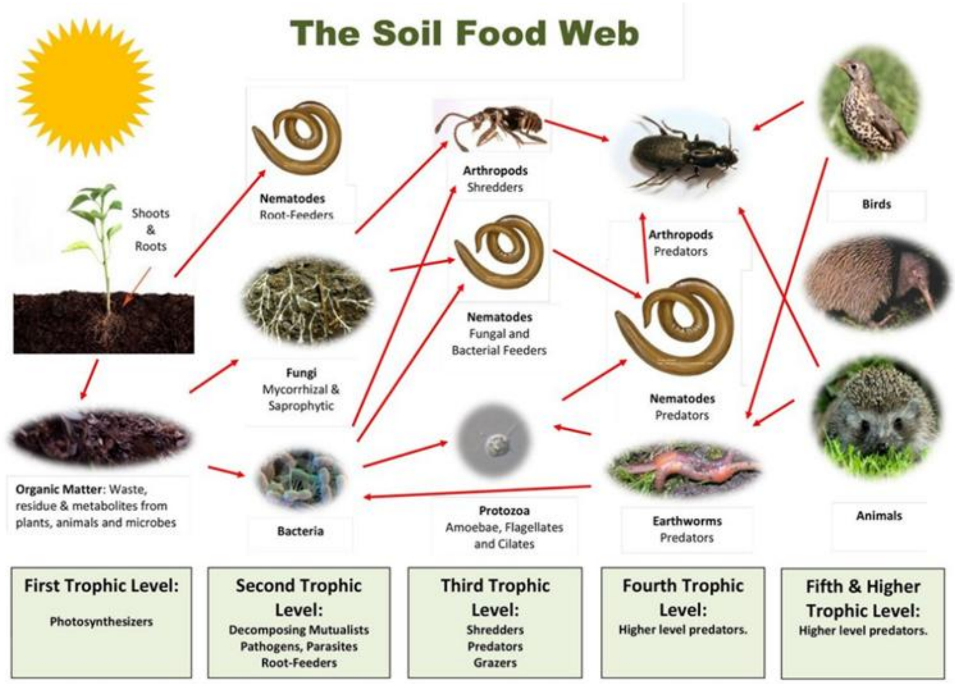


Figure 31: The soil food web. (Soil Food Web New Zealand, 2024)
https://www.soilfoodweb.co.nz/benefits-of-a-health-foodweb

The energy to fuel the soil food web is obtained from the sun by **primary producers** through the conversion of carbon dioxide from the atmosphere into sugars. Primary producers are mainly photosynthesizing plants. This energy is introduced to the soil through the dropping of dead plant parts (leaves, stems, bark, roots).

For the remainder of the soil food web the trophic interactions are executed by heterotrophic organisms, organisms that cannot produce their own food, instead taking nutrition from other sources of organic carbon. These organisms are collectively called consumers. Organic energy and nutrients in dead plant parts are used or released by decay organisms that are called decomposers. Many species of bacteria and fungi are decomposers. **Detritivores** are 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.

6.5 Learning Activity

Soil Organisms

The berlese funnel method is used for extracting invertebrates from soil. It is suitable for collecting earthworms, mites, springtails, centipedes, millipedes, and beetles. It uses a heat source (in this case a light bulb) to dry the sample, forcing the insects through a screen and into a jar of preserving fluid. The detailed lesson plan is found here. https://arboretum.harvard.edu/wp-content/uploads/2020/07/berlese-funnel-how-to.pdf

Activity Description

1. Construct a berlese funnel by cutting a 2 L pop bottle in half. Invert the top half into the bottom half of the pop bottle (to hold the inverted top half). See provided image.
2. Bend down the corners of the window screen so it fits snugly inside the wide end of the funnel. Cut and pinch numerous slits so larger animals can crawl through.
3. Collect several handfuls of L, F, H horizons and put them on top of the screen.
4. Pour alcohol 1-2 cm deep into a small collection vessel that will sit in the bottom half of the pop bottle.
5. Carefully reset the funnel on top of the bottom half of the bottle.
6. Move a lamp/lightbulb at least 15 cm away from the funnel.
7. Allow the soil to dry slowly under the light (about 3 days).
8. Pour the contents of the collection vessel into a Petri dish.
9. Examine the contents. Use a magnifying glass to examine smaller organisms.

7.0 Soil Water

Water occupies one half of soil pore space, constituting up to 25% of the total volume of soil. Water can reach soil through precipitation, irrigation or through seepage from ground and surface water. Once in soil, despite the pull of gravity, water can be stored for a long period of time, providing a moisture reservoir which is essential for the growth of plants and soil organisms. Soil water influences many processes including gas exchange between soil and the atmosphere, the movement of nutrients to plant roots, weathering of minerals, decomposition of organic matter and the leaching of nutrients and pollutants to streams and lakes. Water in soil behaves quite differently from water in a drinking glass or an open body of water because of its association with soil particles. The attraction between water molecules and soil colloids restricts some of the movement of water to plant roots and through the soil profile.

7.1 Properties of Water – Cohesion and Adhesion

Water is a simple molecule, two hydrogen atoms and one oxygen atom, H_2O, yet its unique structure is what gives it the ability to influence soil processes. The hydrogen atoms are attached to the oxygen atom in a V-shaped arrangement which makes water a polar molecule, positive on the hydrogen side and negative on the oxygen side (see Figure 32).

The structure of the water molecule causes the negatively charged oxygen atom of one water molecule to be attracted to the positively charged hydrogen atom of another water molecule. This bond is known as a hydrogen bond and effectively links the water molecules together in a process called cohesion. This phenomena of water molecules being attracted more to each other than the air around them is often referred to as surface tension. A bead of water sitting on a pane of glass is an example of surface tension. The positively charged hydrogen atoms of water molecules are also attracted to the negative charges on soil particles. This process is called adhesion and these forces are much stronger than cohesion as water molecules are tightly held onto the soil. Adhesion and cohesion work together to allow soil particles to hold water and to allow water movement through the soil. Water molecules that are farther away from soil particles are less attracted to the soil and therefore are more mobile.

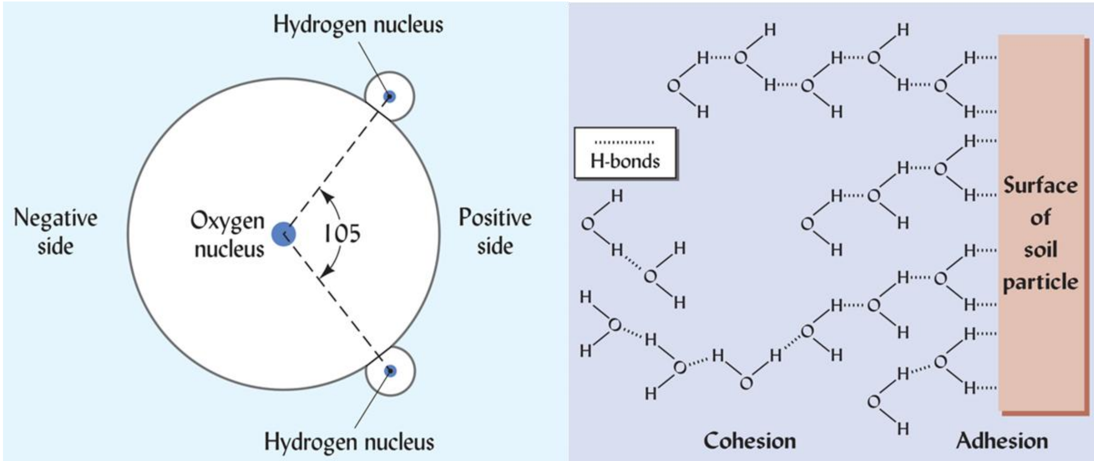


Figure 32: Two-dimensional representation of a water molecule. The forces of cohesion (between water molecules) and adhesion (between water and solid surface) in a soil water system. The forces are largely a result of H-bonding shown as broken lines. (adapted from Weil and Brady, 2017)

7.2 Water Movement in Soil – Soil Water Potential

Water moves in soil because of differences in energy levels between water molecules in adjacent locations of the soil profile. Water molecules in a wet soil have a high energy level and are able to move easily when compared to water molecules in a dry soil that have a low energy level and are held more tightly to soil particles. The ability of water to move in soil is called the soil water potential. Water moves in soil from an area of high water potential to an area of low water potential.

There are three main forces that effect the movement of water in soil.

- Matric forces are those related to cohesion and adhesion and the **capillary** mechanism of water movement. The movement of water up a wick is a good visualization of matric forces and capillary movement. Water is attracted to the wick through adhesion and the long line of water molecules that are pulled up the wick are due to cohesion. In the same way water can move through soil pore space with the matric (adhesion and cohesion) forces providing the energy for capillary movement. Capillary movement of water in soil can be upwards against gravity and depends on the pore size and connectedness of the soil pore space. Finer textured soils with more micropores have greater vertical or horizontal movement of water away from free standing water than courser textured sands, but the movement of water will be slower due to the small pore size (see Figure 33).

- Osmotic forces influence how water moves in soil as a result of dissolved ions in soil solution. Water moves from an area of low ionic concentration (high energy) to an area of high ionic concentration (low energy). Osmotic water potential is a result of the attraction of water to dissolved ions, which reduce the energy level of water in soil solution. While the dissolved ion concentrations in most soils is low and does not affect water movement, osmotic potential can impact the uptake of water by plant roots in saline soils. For example, a buildup of salt in soil from excessive fertilizer application can affect the ability of roots to take up water from the soil, actually drawing water from the roots back into the soil.

- Gravitational forces are the result of the pull of gravity, and are defined relative to a specific elevation (e.g., top of the soil profile). Following heavy rainfall or snowmelt, gravity moves excess water from upper soil horizons and recharges groundwater deeper in the soil. Gravity plays a major role in the movement of water in soil macropores that are too large for matric forces to dominate.

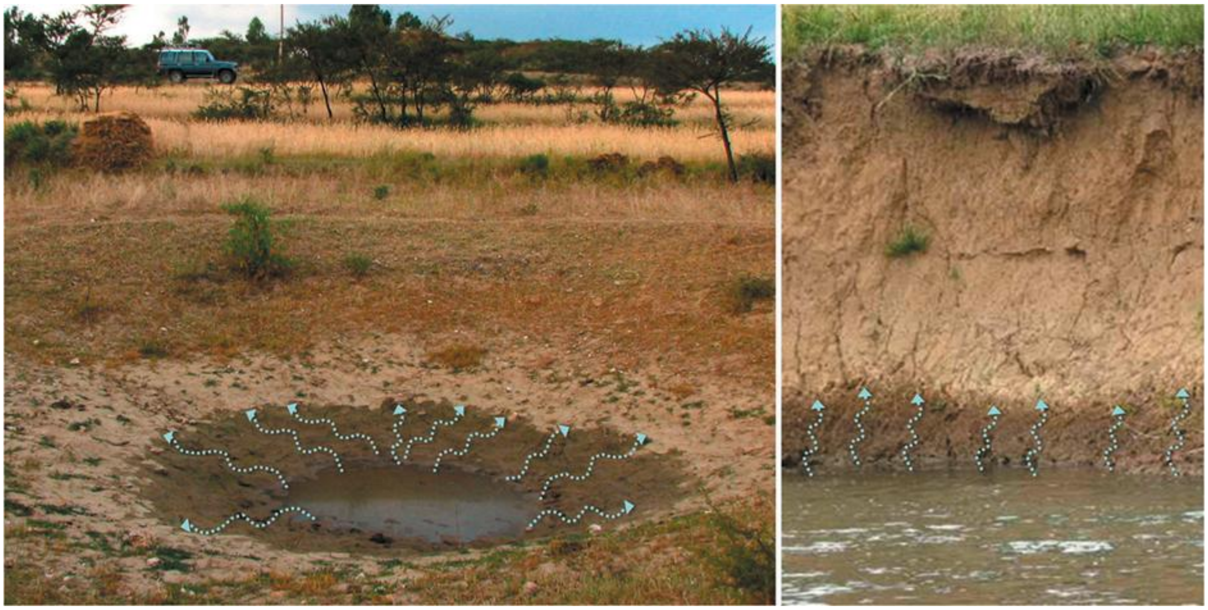


Figure 33: Capillary water movement in soil due to adhesion and cohesion forces. (Weil and Brady, 2017)

Contrasting soils from different textural classes highlights the difference between matric and gravitational forces. Sands have more macropores so water drains very quickly after a rainfall because of the force of gravity. Clay soils have many micropores and the films of water that surround clay particles are held by matric forces stronger than the force of gravity, even long after rain has stopped falling.

For any given soil, the soil total water potential is the sum of the soil water forces, and soil water will flow from locations of high total potential to locations of low total potential. The gravitational forces are trying to force water out of the soil and the matric and osmotic forces attract water to the soil. Not every soil water potential component contributes to the total soil water potential in all circumstances. For example, below the water table, matric potential is zero because the forces that change matric potential, adsorption and capillarity, are very weak in saturated soil.

7.3 Types of Soil Water – Soil Water Content

Soil water content is the amount of water present in soil as measured as a volume or mass of water per the total volume or mass of soil (see Figure 34). When all the pores are filled with water the soil is water saturated and at its maximum retentive capacity. At this stage the water molecules closest to the soil particles are held more strongly than those farther away.

Since water molecules in macropores are farther away from the soil particles, and more weakly held, the gravitational force is greater than matric force and water starts to drain from the soil. The water that drains from the soil is called gravitational water and cannot be used by plant roots or soil organisms because the water drains so quickly. After the soil has drained, the water molecules are held in micropores by the matric forces of adhesion and cohesion. The water content when the gravitational water stops draining is called the field capacity. Field capacity for any given soil is described as the amount of water left in soil two to three days after being saturated and allowed to freely drain by gravity.

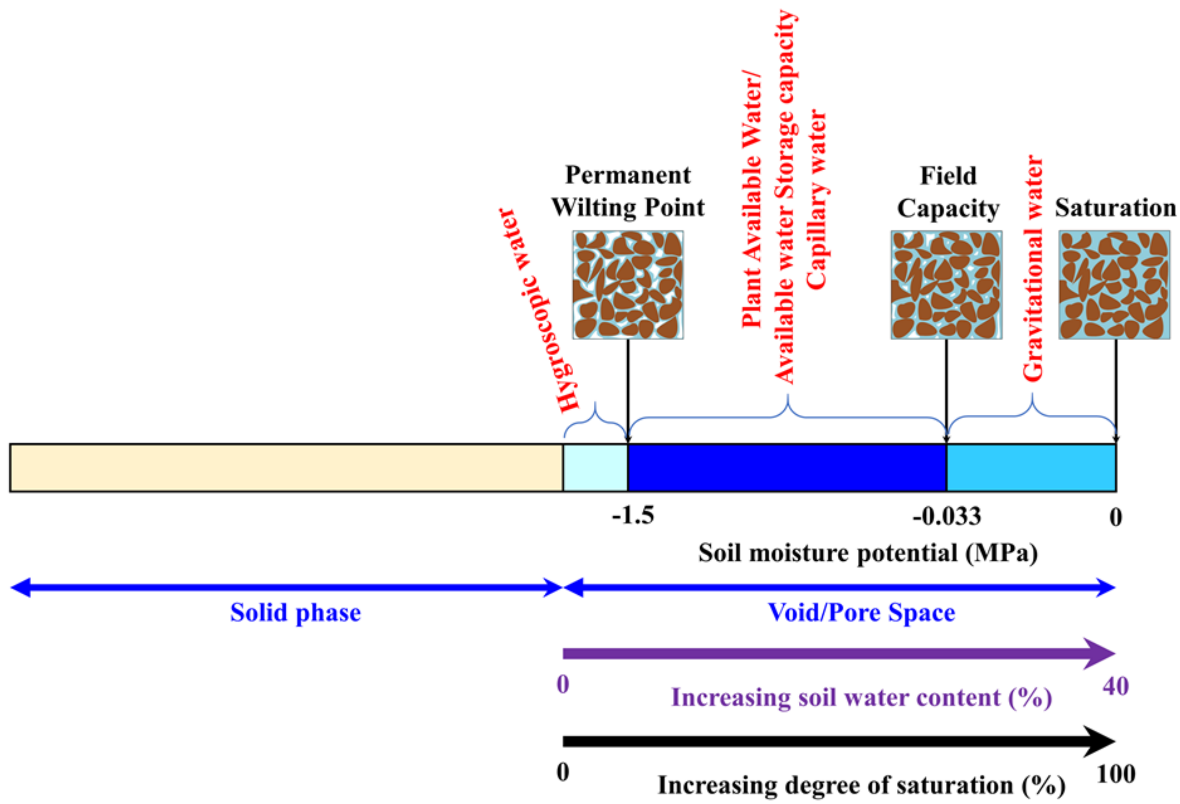


Figure 34: Common terms used to describe soil water content. (Krzic et al., 2021)
https://openpress.usask.ca/app/uploads/sites/81/2020/08/Fig_4.5.png

At field capacity plant roots can take up water from the soil. As the soil starts to dry further the remaining water is held at progressively stronger tension by the soil particles. At a certain point the soil reaches a stage where the plants cannot take up any more water from soil. At the wilting point the soil water is held so tightly that plants are unable to extract the water and therefore wilt. Plant roots can only exert pressures up to a certain extent and can uptake a limited amount of the water present in soil. Between field capacity and the wilting point plants can utilize the water held in the soil. The amount of water plants can extract is known as plant available water or capillary water.

As the soil dries further, water molecules are held so tightly to the soil particles that plant roots cannot exert enough force to take water out of the soil. This water is held in thin films surrounding the soil particles and much of it is considered non-liquid, only able to move in the vapour phase by evaporation. This is known as hygroscopic water and represents a small amount of water found in soil.

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. 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.

7.4 Learning Activity

Perkin' through the pores

In this activity students will determine the water holding and draining capacities of different soils and will investigate how organic matter increases the amount of water soil will hold. The detailed lesson plan is found here. https://www.soils4kids.org/files/s4k/perkin.pdf

Activity Description

1. Collect and dry mineral soil samples with varied soil textures, from sand to clay.
2. Cut a 2 L pop bottle in half. Invert the top half into the bottom half of the pop bottle (to hold the inverted top half).
3. Place one coffee filter into the funnel and then add 1 cup of soil. Cover the sample with another filter. Pour 2 cups of water into the funnel.
4. Measure the amount of time it takes until most of the water has gone through the soil sample.
5. Compare the time it took for water to percolate through each sample.
6. Pour out and measure the volume of water that percolated through each sample.
7. Duplicate the experiment, this time, add one cup of potting soil on top of the upper filter of each mineral soil sample.
8. Record data and compare the percolation time and volume for each sample.

8.0 Soil Classification

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 transitions either gradually or abruptly from one type of soil to another across the landscape. In addition, while the identification and classification of plants and animals follow the same approach around the world, different countries have different systems for soil classification. Many national soil classification systems were developed because they are focused on the specific characteristics of the soils within their own country and based on national soil surveys and mapping.

8.1 The Why and How of Soil Classification

The classification and subsequent mapping of soils is fundamental information that is required to determine the state of the natural environment and potential land use by humans. Any activity involving soil, from a farmer or forester determining which crop or tree to plant, to an engineer building a highway or building will benefit from soil classification. The grouping of similar soils and the separation of meaningful differences between soils allows us to organize soils information and communicate that knowledge to others.

At any specific location the soil forming factors and processes lead to the development of horizons with distinct physical, chemical and biological properties. These observed and measured properties are collected through soil surveys and then used to group soils by diagnostic horizons allowing the classification of soils into different hierarchal categories. This naming system is called soil taxonomy. Soil classification makes it simpler to understand the associations among soils within a given area and between different areas and their relationship with their environments.

8.2 The Canadian System of Soil Classification

In Canada, the soil classification system categorizes soil profiles into five main hierarchal levels (see Figure 35). Soil Orders are the highest level and the most general grouping. There are ten Orders in the Canadian Soil Classification System: Chernozemic, Solonetzic, Podzolic, Luvisolic, Brunisol, Gleysolic, Regosolic, Vertisolic, Cryosolic and Organic. Orders are based on the presence or absence of diagnostic horizons that reflect the properties of the profile, the nature of the overall soil environment and the effects of the dominant soil-forming processes (see Table 7).

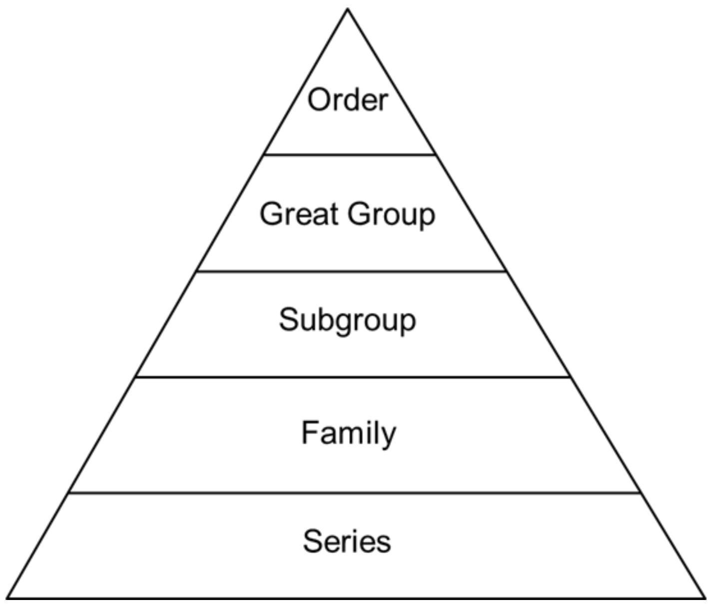


Figure 35: Levels in the Canadian System of Soil Classification ordered from highest (the most general) to lowest (the most specific). (Agriculture and Agri-Food Canada, 1998).
https://sis.agr.gc.ca/cansis/taxa/cssc3/chpt01.html#attributes

Each order is further divided by Great Group, Subgroup, Family and Series. The lower levels in the classification fit within the higher levels. Great Groups reflect differences in the strengths of the major processes or a major contribution of a process in addition to the dominant one. Subgroup profiles are differentiated on the basis of the kind and arrangement of horizons that reflect a conformity to the central concept of the Great Group, a gradation towards another soil Order, or the presence of a special horizon within the profile. Families are differentiated on the basis of the parent material characteristics such as texture, mineralogy, depth, pH and on differences in soil climatic factors. Series within a family are differentiated on the basis of detailed features of the profile. Profiles belonging to a series have similar kinds and arrangements of horizons whose specific soil properties fall into a relatively narrow and well defined range.

Table 7: Diagnostic horizons and main characteristics of the soil Orders in the Canadian System of Soil Classification. (Canadian Society of Soil Science, 2020). https://soilsofcanada.ca/orders/orders.php

Soil Order	Diagnostic Horizon	Comments
Brunisolic	Bm	A forest soil whose properties are not strongly enough developed to meet the criteria for the Luvisolic or Podzolic Orders.
Chernozemic	Ah, Ap, Ahe	A grassland soil whose diagnostic horizon is formed by high levels of organic matter additions from the roots of grasses.
Cryosolic	By, Cy, Cz	A soil of arctic and tundra regions; characterized by presence of **permafrost**.
Gleysolic	Bg, Cg	A wetland soil. Found throughout Canada wherever temporary or permanent water saturation cause formation of gleyed features in the profile.

Luvisolic	Bt	A forest soil found in areas with parent materials derived from sedimentary rocks. Dominant process is eluviation of clay from the Ae horizon and its deposition in the Bt horizon.
Organic	O horizon	Organic soils are associated with the accumulation of organic materials (peat) in water-saturated conditions. They are most commonly associated with the Boreal forest and tundra regions.
Podzolic	Bf or Bh	A forest soil normally associated with coniferous vegetation on igneous-rock derived parent materials. High acidity in the A horizon results in formation of a bleached Ae horizon and deposition of iron and aluminum in the B horizon.
Regosolic	No B horizon	A minimally developed soil. Found throughout Canada wherever conditions prevent the formation of B horizons (unstable slopes, sand dunes, floodplains etc.).
Solonetzic	Bn or Bnt	A grassland soil with high sodium levels in the B horizon; usually associated with a clay-rich B horizon and often with saline C horizon material.
Vertisolic	Bss, or Css and Bv	Associated with high clay glacio-lacustrine landscapes; characterized by shrinking and swelling of clays.

Understanding the distribution of soil types across Canada and Ontario (see Figures 36 and 37) assist policy makers and land managers to better understand the suitability of soils for various purposes. The maps below show the geographical distribution of soil Orders. Of the ten soil Orders seven are present in Ontario. These are Brunisolic, Cryosolic, Gleysolic, Luvisolic, Organic, Podzolic and Regosolic soils.

Soil development is ongoing and the Canadian System of Soil Classification continues to be developed as more knowledge becomes available. Advances in remote sensing technologies and geographical information systems (GIS) has led to the digital soil mapping (DSM) approaches. The transition to DSM will provide soil information that is more accurate and precise, and is less time consuming and expensive than traditional soil survey activities.

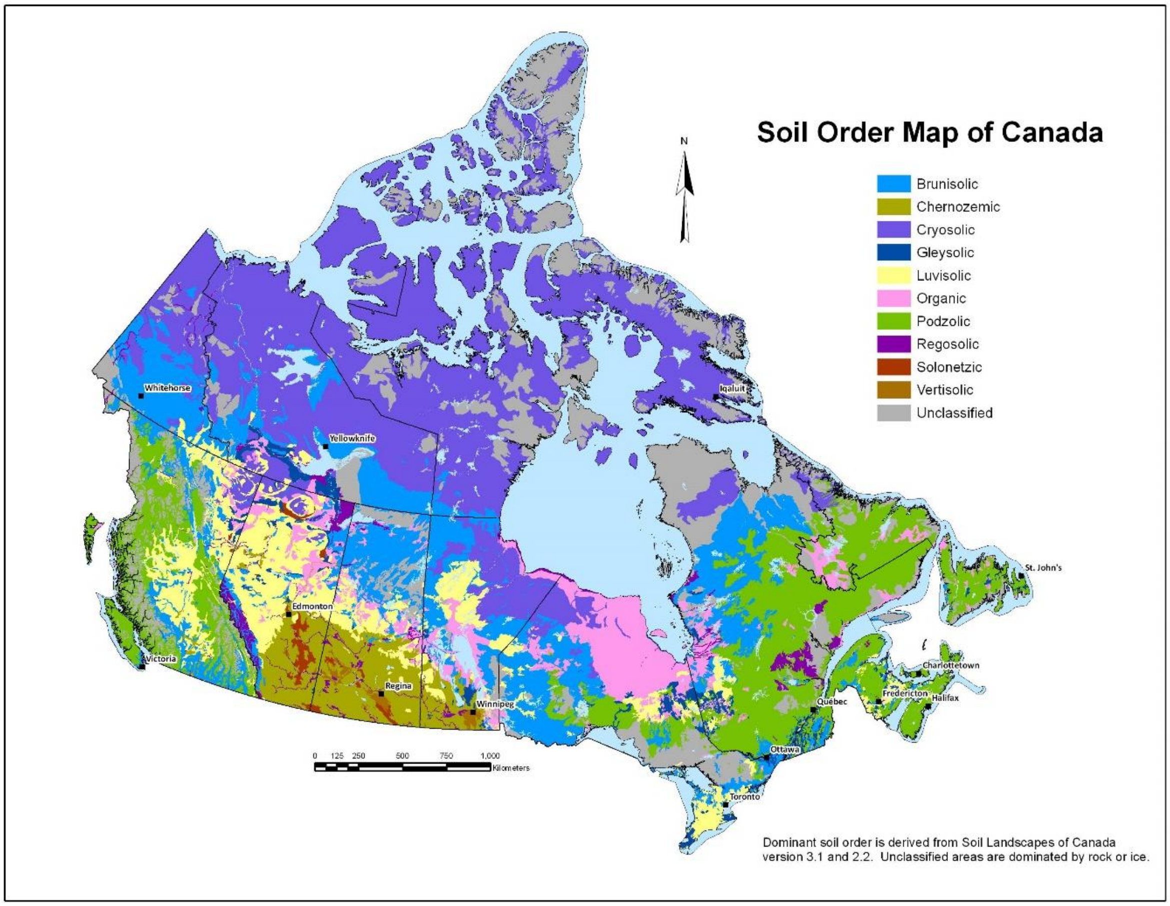


Figure 36: Soil Order map of Canada. (Canadian Society of Soil Science, 2020). https://soilsofcanada.ca/

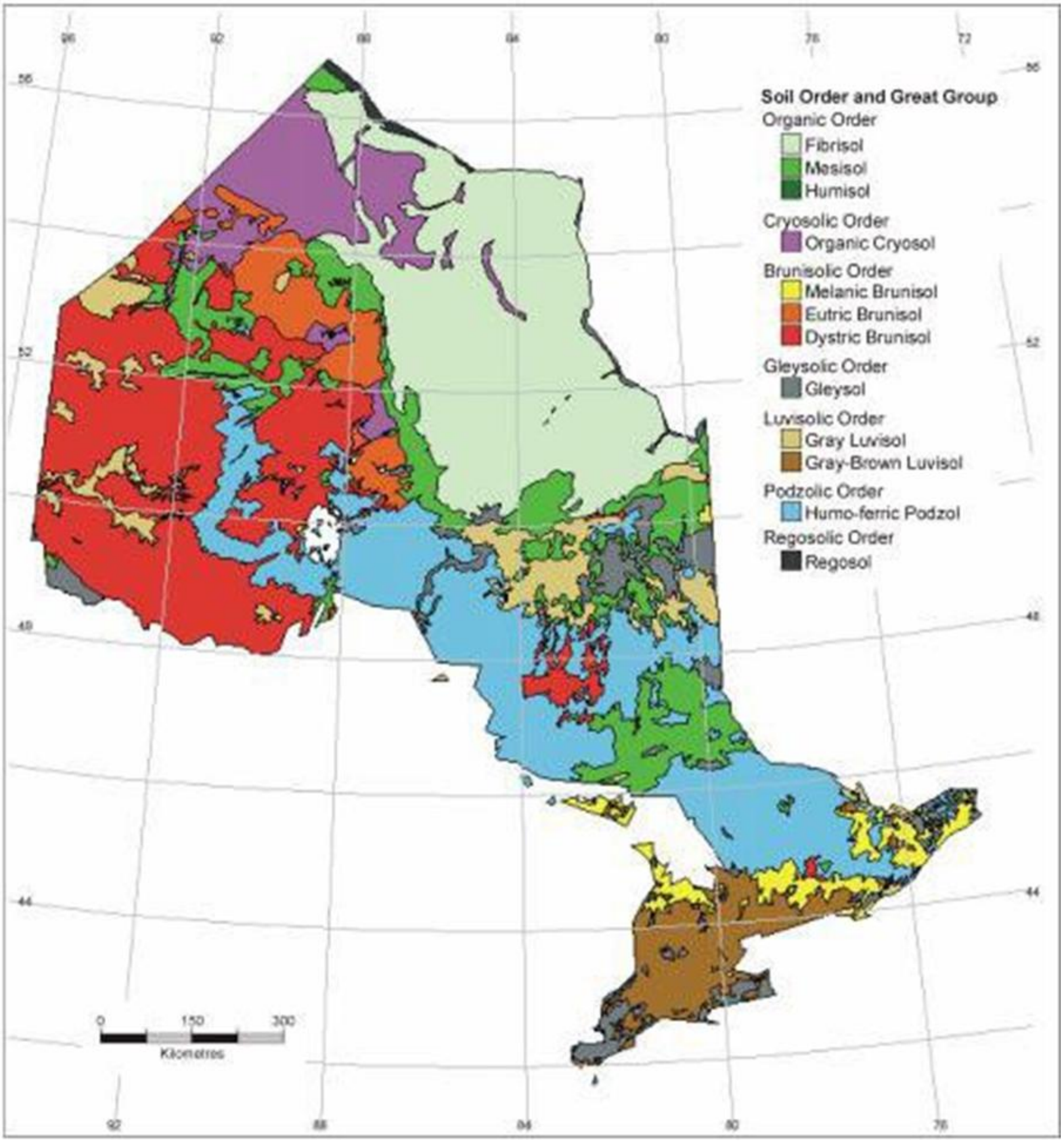


Figure 37: Soil Orders and Great Groups in Ontario. (Baldwin et al., 2007)
https://www.ubcpress.ca/asset/12524/1/9780774807494.pdf

8.3. Learning Activity

<u>Canada's Best Soil</u>

In this activity, students will learn about Canada's Soil Orders, make a class presentation, and then cast a vote for their favourite soil order. The detailed lesson plan is found here.
https://lfs-soil4youth.sites.olt.ubc.ca/files/2015/05/LessonPlan6-SoilOrderCompetition-Oct2013.pdf

Activity Description

1. Split the class into groups and assign each group one of Canada's ten Soil Orders.
2. As a group the students will prepare a short presentation to make to the rest of the class as part of a Canada's Best Soil competition.
3. Students use online resources to prepare their presentation: University of British Columbia Soilweb Soil Orders videos https://classification.soilweb.ca/ and Canadian Soil Science Society Soils of Canada Learning Resource https://soilsofcanada.ca/orders/index.php
4. Student presentations should include Soil Order: value (land use, ecosystem service), distribution across Canada, diagnostic horizon, appearance, uniqueness, other notable fun facts. Students use their creativity to convince the class that their Order is the best.
5. Students cast a vote. The winning group receives a soil related prize.

9.0 Glossary

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

Alkalinity: the level of an alkali (a substance with the opposite effect or chemical behaviour to an acid) in substances such as water or soil

Boulder: a coarse fragment found in soil > 60 cm in diameter

Capillary: the movement of water through soil pore space due to matric forces (adhesion and cohesion)

Carbon pools: reservoirs of carbon that have the capacity to both take in and release carbon

Carbonation: the process of carbonic acid (water combined with carbon dioxide) dissolving minerals in rock

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

Centimoles: one mole of any element is the atomic mass of the element, a centimole is equal to 0.01 moles

Chemical weathering: the breakdown of rock by chemical forces

Chroma: purity or intensity of colour

Clay: mineral soil particles < 0.002 mm in diameter

Climate: the weather conditions prevailing in an area

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

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

Decomposers: organisms that decompose organic material

Detrital: organic matter made up of the decomposing remains of animals and plants

Erosion: the gradual wearing a way of something by natural forces such as water, wind or ice

Detritivores: organisms, such as a bacterium, fungus, or insect, that feed on dead plant or animal matter

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

Fertility: the ability of soil to supply nutrients to plants in optimal quantities to promote growth

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

Gleying: gray and blue soil colour caused by the reduction of iron and other elements, caused by anaerobic conditions due to poor drainage conditions, waterlogging and a high water table

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

Herbivores: animals that feeds only on plants

Horizon: a specific layer in the soil that runs approximately parallel to the ground surface and has different properties from horizons above and below.

Hue: a colour or shade

Humus: an organic soil horizon at an upland site characterized by decomposed organic matter in which the original structures are indiscernible

Hydrolysis: a chemical reaction where water loosens the chemical bonds within a mineral, produces a different mineral in addition to ions

Igneous: a type of rock formed from solidified from lava or magma

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

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

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

Macrobiota: soil organisms visible to the naked eye (> 2 mm in size) that dig in the soil for shelter and feed on, or in the soil

Mesobiota: soil organisms 0.1 - 2 mm in size, including vertebrates such as mice, moles, and groundhogs and invertebrates such as ants, termites, earthworms and snails

Metamorphic: rock that has undergone transformation by heat and pressure

Microbiota: soil organisms not visible to the naked eye (< 0.1 mm in size) that generally live within the soil pores, including algae, bacteria and fungi

Mottles: spots or blotches of red, yellow or orange colour interspersed with the dominant soil color, caused by the oxidation of iron due to a fluctuating soil water table

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

Nutrient(s): 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

Oxidation: a process when free oxygen (i.e., oxygen not bound up in molecules with other elements) is involved in chemical reactions

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

Parent material(s): the underlying geological material in which soil horizons form

Pedon: the basic sampling unit in a soil survey, a hexagonal column measuring 1 to 10 square meters in top surface area

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 (H+) ions in soil solution that is expressed as a negative logarithm (pH = - log [H+])

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

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

Sand: mineral soil particles 0.05 - 2mm in diameter

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

Sedimentary: rock that has formed from sediments weathered from other rocks that are compacted and cemented together.

Sediments: the loose collection of material that is the product of weathering and erosion

Silt: mineral soil particles 0.002 - 0.05 mm in diameter

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

Soil exchange complex: cations that are held close to the soil particle because soil is negatively charged

Soil profile: consists of the combined sequence of all the horizons in a soil, a vertical section of the soil from the ground surface downwards to where the soil meets the underlying bedrock

Soil solution: the water surrounding the soil particles which contains dissolved nutrients

Stone: a coarse fragment found in soil 25 – 60 cm in diameter

Taxonomy: the classification of something

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

Texture: the percentages of sand, silt and clay in a mineral soil sample.

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

Value: lightness or darkness of colour

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

10.0 Additional Resources

Listed by section:

2.0 Soil: The Connector, Protector, Producer

Applications of Soil - Ontario Envirothon Virtual Lab Video
https://www.youtube.com/watch?v=J80MJhXxxus

Forest Soils - Forests Canada Focus on Forests Activity Sheet
https://assets.ctfassets.net/e09p19lzfrfe/3aQDKCmTNIeFMK070iGIXF/36788c5aaba19be504db14c0817a6862/FOF-07_Forest_Soils.pdf

3.0 Soil Formation

Soil Formation - the soil forming factors - University of British Columbia Soilweb VIdeo
https://www.youtube.com/watch?v=bTzslvAD1Es

4.0 The Physical Properties of Soils

Soil Texture: what is it, why is it important and how to determine it - Forests Canada Video
https://www.youtube.com/watch?v=jfKSQ0uOUNo

Get the Dirt on Soils - soil physical properties: soil compaction and soil bulk density - Forests Canada Video
https://www.youtube.com/watch?v=nHPuDqF7vIo

5.0 The Chemical Properties of Soils

Soil Fertility: A Brief Overview - Forests Canada Video
https://www.youtube.com/watch?v=LLRCjkPsYU4

6.0 The Biological Properties of Soils

Farming Practices: why is soil health important on the farm - Forests Canada Video
https://www.youtube.com/watch?v=GMEhwtO_Ccc

Soil Your Undies - Forests Canada Virtual Lab Activity Sheet
https://assets.ctfassets.net/e09p19lzfrfe/QP3MMcU4SLhECFARugAva/6a87f4358852200dd3b9ef384d844151/Appendix-A-Soil-Your-Undies.pdf

7.0 Soil Water

The Forest Sponge - Forests Canada Focus on Forests Activity Sheet
https://assets.ctfassets.net/e09p19lzfrfe/63MnppQT9OS8sDYebFlzLN/30375116a31d3121c9197ba421875227/FOF_47_The_Forest_Sponge_Layout.pdf
Soil Solutions - Forests Canada Focus on Forests Activity Sheet
https://assets.ctfassets.net/e09p19lzfrfe/3ClgFzcqT2XBDVeg68dioC/00f4d617b2317f0821bf6acc46ac4e02/FOF-79_Soil-Solutions.pdf

8.0 Soil Classification

Soil Detective Work: "reading" a soil profile - Forests Canada Video
https://www.youtube.com/watch?v=IP4JOj7Gpt0

Soil Classification: Soil Orders of Canada - University of British Columbia Soilweb VIDEO
https://classification.soilweb.ca/

Soil Orders - Canadian Soil Science Society Soils of Canada Learning Resource
https://soilsofcanada.ca/orders/index.php

Canadian Soil Classification - Forests Canada Ontario Envirothon Learning Resource
https://assets.ctfassets.net/e09p19lzfrfe/2dpxfjp6vdI3MftSBWjx1T/51be5d219f004c0128464cae1431f4fc/Canadian-Soil-Classification.pdf

Forest Soils of Ontario - Great Lakes Forestry Centre soil monolith collection
https://cfs.nrcan.gc.ca/projects/101

Other soil resources:

Agroecology: feeding the world - Forests Canada Video
https://www.youtube.com/watch?v=LyUL6TJAhpY

Climate Change: the need for action - Forests Canada Video
https://www.youtube.com/watch?v=iGrZpfOMCig

Creating planet friendly food and farms - Forests Canada Video
https://www.youtube.com/watch?v=4tmu7mhkgaY

Ecosystem Restoration - Forests Canada Ontario Envirothon Learning Resource
https://assets.ctfassets.net/e09p19lzfrfe/1Fw41grfo6YbpHE86bXR3L/8d747f29a3d73947d86365dba55c5da5/2022_Ecosystem_Restoration.pdf

Sustainable Agriculture - Forests Canada Video
https://www.youtube.com/watch?v=lRpKmykD68M&t=5s

Sustainable Farming - Forests Canada Ontario Envirothon Learning Resource
https://assets.ctfassets.net/e09p19lzfrfe/5gqQV38KSH9I2GmCzs0zFZ/ce96788a787e4e8b249a538857103da2/FO16_STUDY-GUIDE-FARMING_FA_REV_small.pdf

What Lies Beneath…Your Feet - Forests Canada Ontario Envirothon Learning Resource
https://assets.ctfassets.net/e09p19lzfrfe/43zBh7XRbFY1ezSaKEtqoY/09178b3a88c95e26d2a622f3965e990a/Canadian-Soil-Science-Society.pdf

References

Agriculture and Horticulture Development Board. (2024). Soil organisms stabilise soil structure. Retrieved from: https://ahdb.org.uk/knowledge-library/soil-organisms-stabilise-soil-structure

Baldwin, D. J.B., Deslodges, J.R., Band, L.E. (2007). Physical geography of Ontario. UBC Press. Retrieved from: https://www.ubcpress.ca/asset/12524/1/9780774807494.pdf

Canadian Society of Soil Science. (2020). Soils of Canada. Retrieved from: https://soilsofcanada.ca/imagery-collection/

Carbon Streaming Corporation. (2021). Ecosystem carbon storage. Retrieved from: https://www.visualcapitalist.com/sp/visualizing-carbon-storage-in-earths-ecosystems/

Colorado State University. (2022). Estimating soil texture: sandy, loamy, or clayey. CMG GardenNotes #214. Retrieved from: https://cmg.extension.colostate.edu/Gardennotes/214.pdf

Earth Floor. (2005). The rock cycle. Retrieved from: http://www.cotf.edu/ete/modules/msese/earthsysflr/rock.html

Food and Agriculture Organization of the United Nations. (2015). Soil functions. Retrieved from: https://www.fao.org/soils-2015/resources/infographics/en/

Harvard Arboretum. (2020). The berlese funnel - Soil Science Society of America Soils4Teachers. Retrieved from: https://arboretum.harvard.edu/wp-content/uploads/2020/07/berlese-funnel-how-to.pdf

Hazlett, P., Emilson, C., Lawrence, G., Fernandez, I., Ouimet, R., Bailey, S. (2020). Reversal of forest soil acidification in the northeastern United States and eastern Canada: site and soil factors contributing to recovery. Soil Systems, 4(3), 54. Retrieved from: https://www.mdpi.com/2571-8789/4/3/54

Heck, R.J., Kroetsch, D.J., Lee, H.T., Leadbeater, D.A., Wilson, E.A., Winstone, B.C. (2017). Characterizing sites, soils & substrates in Ontario. Volume 1 - Field Description Manual. Published by the School of Environmental Sciences, University of Guelph.

Hutchinson, G.E. (1965) The ecological theater and the evolutionary play. Yale University Press, New Haven, CT.

Krzic, M., Walley, F.L., Diochon, A., Paré, M.C. and Farrell, R.E. (Eds.). (2021). Digging into Canadian soils: an introduction to soil science. Pinawa, MB: Canadian Society of Soil Science. Retrieved from: https://openpress.usask.ca/soilscience/

Michigan State University Extension Agriculture. (2013). Knowing nutrient mobility is helpful in diagnosing plant nutrient deficiencies. Retrieved from: https://www.canr.msu.edu/news/knowing_nutrient_mobility_is_helpful_in_diagnosing_plant_nutrient_deficienc

Ontario Centre for Soil Resource Evaluation. (1993). Field Manual for Describing Soils in Ontario. 4th Edition. Ontario Centre for Soil Resource Evaluation. Publication No. 93-1.

Panchuk, K. (2021). Physical Geology - H5P Edition V1.1. Retrieved from: https://pressbooks.bccampus.ca/physicalgeologyh5p/chapter/17-3-glacial-deposits/

Ritchey, E. L., McGrath, J. M., Gehring, D. (2015). Determining Soil Texture by Feel. Agriculture and Natural Resources Publications. 139. Retrieved from: https://uknowledge.uky.edu/cgi/viewcontent.cgi?article=1139&context=anr_reports

RX Green Technologies. (n.d.). Plant-substrate interaction. Retrieved from: https://www.rxgreentechnologies.com/wp-content/uploads/2020/02/Plant-Substrate_Interaction-1.pdf

Soil Food Web New Zealand. (2024). The soil food web. Retrieved from: https://www.soilfoodweb.co.nz/benefits-of-a-health-foodweb

University of British Columbia Soilweb. (n.d.). Soil order competition. Retrieved from: https://lfs-soil4youth.sites.olt.ubc.ca/files/2015/05/LessonPlan6-SoilOrderCompetition-Oct2013.pdf

University of Georgia Extension. (2022). Cation exchange capacity and base saturation. Retrieved from: https://extension.uga.edu/publications/detail.html?number=C1040&title=cation-exchange-capacity-and-base-saturation

Utah State University, Agriculture in the Classroom. (n.d.). Perkin' through the pores. Retrieved from: https://www.soils4kids.org/files/s4k/perkin.pdf

WeatherStem. (2017). Soil development over time. Retrieved from: https://learn.weatherstem.com/modules/learn/lessons/85/06.html

Weil, R.R. and Brady, N.C. (2017). The Nature and Properties of Soils. 15th Edition, Pearson, New York.

Wikimedia Commons. (2007). The Munsell colour system. Retrieved from: https://commons.wikimedia.org/wiki/File: Munsell-system.svg

Wikipedia. (2019). The nitrogen cycle. Retrieved from: https://en.wikipedia.org/wiki/Nitrogen_cycle#/media/File:Nitrogen_Cycle_2.svg