What Lies Beneath...Your Feet!

Ontario Envirothon Supplementary Resource

This resource was developed in partnership and with support from the Canadian Soil Science Society.

FORESTS ONTARIO

Acknowledgements

Forests Ontario would like to acknowledge the contribution of the Canadian Society of Soil Sciences (CSSS) in the preparation of this document.

The Canadian Society of Soil Science (CSSS) is a non-governmental, non-profit organization for scientists, engineers, technologists, administrators, and students involved in professional soil science. Its goal is to nurture the discipline of soil science in Canada and ensure its relevance in the future. It works to achieve this goal by:

- promoting the wise use of soil for the benefit of all society;
- promoting information and technology exchange among people in the professional soil science community;
- fostering the integration of students into the professional soil science community;
- providing a link between soil scientists in the private, public, and university sectors;
- disseminating research and the practical application of findings in soil science;
- representing the Canadian soil science community in international organizations and meetings; and
- celebrating the accomplishments of Canadian soil scientists.

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SECTION 1 Introduction to Soil

Prepared by Daryl Degasse

What is soil?

Although everyone has an idea of what soil is, it can have many definitions depending on who is talking about it and why they want to use it.

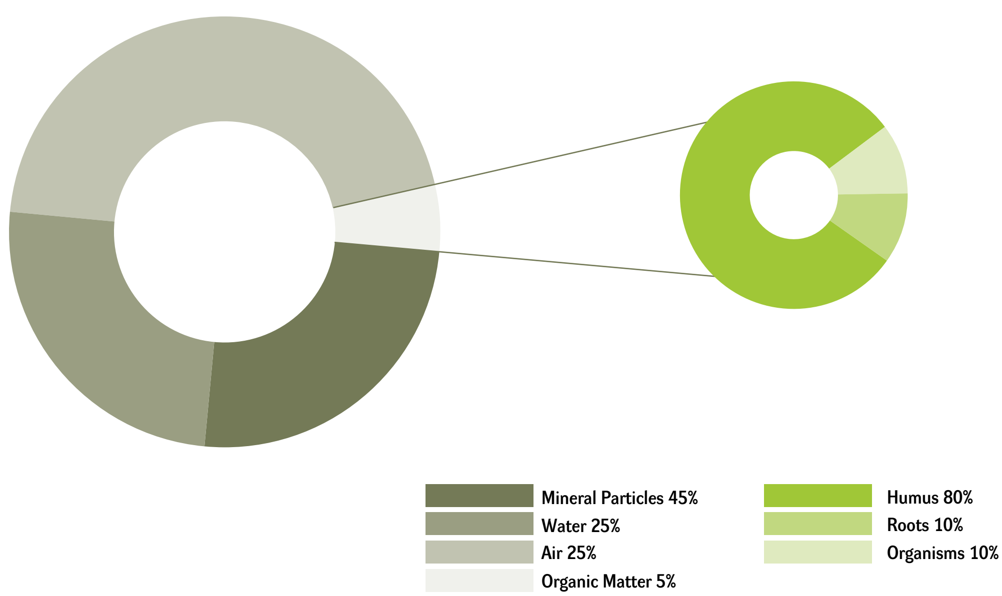
- *Pedologists* study the evolution and function of soils.
- *Agronomists* study the capability of soils for growing different crops.
- *Geomorphologists* study why landscapes look the way they do.
- *Engineers* study the suitability of soils as substrates for structures such as roads, buildings and other structures.

Soil is defined by **Canadian System of Soil Classification, 3rd edition** as the naturally occurring, unconsolidated mineral or organic material, at least 10 cm thick, which occurs at the earth's surface and is capable of supporting plant growth. The average depth of soil is almost a metre, but compared to the diameter of earth (~6.3 million meters), it represents just a tiny fraction. It can be considered the skin of the earth.

Soils may also be thought of as a porous media, like a sponge, containing both:

- Solids—the solid particles that make up the soil skeleton, including:
  - mineral grains
  - organic matter (both living and dead)
- Voids—the "empty" spaces between the solid particles that contain:
  - liquids ("water")
  - gases ("air")

Very generally, these components are considered to occur in the following proportions:



source: http://www.physicalgeography.net/fundamentals/10t.html

Where does soil come from?

Soil is considered to have formed upon a parent material (one of the soil forming *factors*). Although this parent material is often thought of as the loose weathered material from the underlying bedrock, this is not always the case in Canada where most parent material is sediment deposited as a result of glaciation.

Glaciers abraded and quarried the underlying bedrock, pulverizing it into material that was subsequently transported and deposited (Fig. 1) and then re-worked by the actions of water and wind. The resulting deposits contain materials ranging in size from boulders down through sand, silt and clay that form the parent material upon which today's soils are forming (Fig. 2). We therefore see soils formed in geologically uniform areas that are distinctly different because they formed on different glacial features such as drumlins, eskers, moraines and spillways.

FIGURE 1. *A glacier in Greenland. Note the dark stripes on the glacier, representing eroded material being incorporated into the glacial ice.* **(Photo: Wikimedia)**

FIGURE 2. *Glacially deposited material in an esker near St. Jacob's, Ontario. Note the wide range of grain sizes, from fine sand to medium boulders.* (**Photo: http://tcc.customer.sentex.ca/GT/clastic_dyke4.jpg**)

Soil is material that has been subjected to and shows effects of environmental *factors* as summarized by what is known as the *CLORPT* Equation (or soil-forming equation) where:

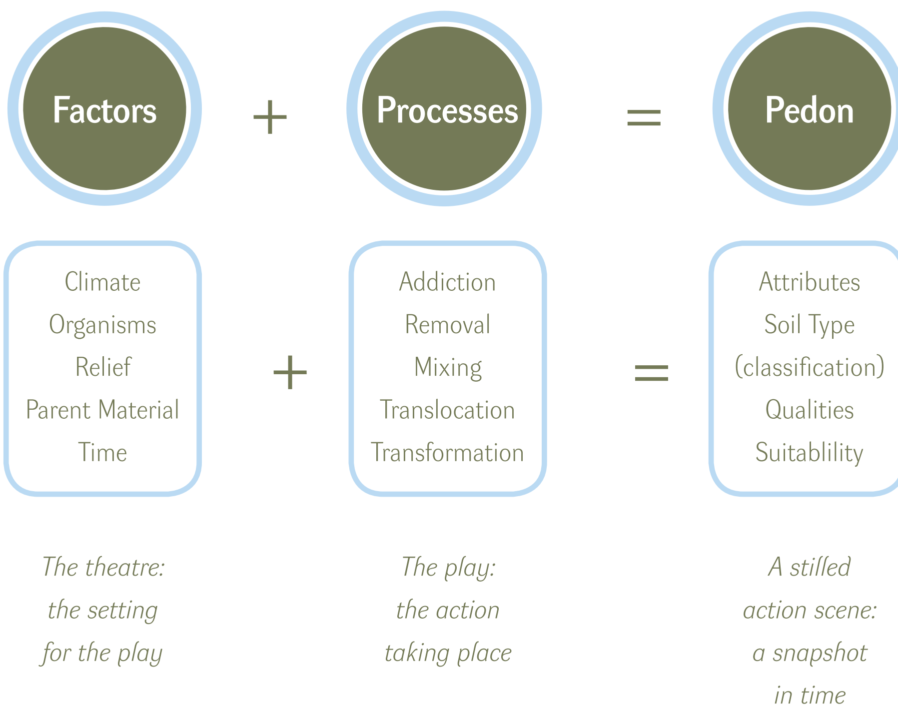
- *CL* represents the climatic effects, including water and temperature
- *O* represents macro- and micro-organisms
- *R* represents the relief of the landscape
- *P* represents the effects of the parent material on which the soil is forming
- *T* represents the period of time over which the soil has been forming

Soil is also affected by a series of naturally occurring *processes* including:

- *Additions* including things such as falling leaves and windblown dust
- *Removals* such as organic matter via decay or sediment via erosion
- *Mixing* through actions such as burrowing animals or frost heaving
- *Translocations* such as fine soil particles washing downwards
- *Transformations* such as the decay of organic matter

Together, these *factors* and *processes* act together to develop the soil we see.

Soil Formation: Factors & Processes



(modified from Hutchinson 1965)

Refer to the **Section 2: Introduction to Soil** for more information.

Why is soil important?

Soil performs many critical functions in almost every ecosystem (whether a farm, forest, prairie, marsh, suburban watershed or urban environment). General roles that soils play:

- It serves as media for growth of all kinds of plants, including the agricultural crops that feed the world population, supporting them physically and physiologically. Approximately 95% of all food comes from the soil.
- It modifies the atmosphere by emitting and absorbing gases. Carbon dioxide is often mentioned as an important greenhouse gas. People find it surprising that the soil contains more organic carbon than both the ground vegetation and atmosphere combined. Other important greenhouse gases associated with the soil include methane and water vapor. Refer to **Section 5: Soils, Land Use and Climate Change** lesson plan for more information.
- It provides habitat for animals that live in the soil (such as groundhogs and mice) to micro-organisms (such as bacteria and fungi), that account for most of the living things on Earth. Soils host approximately one quarter of the planet's total biodiversity. There are more organisms in a single tablespoon of healthy soil than there are people on Earth.
- Soil absorbs, holds, releases, alters, and purifies most of the water in terrestrial systems, therefore acing as a living filter to clean water before it moves into an aquifer.
- It processes recycled nutrients, including carbon, nitrogen and phosphorus, so that living things can use them over and over again.
- It serves as engineering media for construction of building foundations, roadbeds, dams and other structures.
- It preserves or destroys artifacts of human endeavors as studied through archeology.

Threats to the soil

Soil is one of the Earth's most critical resources. In fact, there would be no life without it. However, soil and the critical roles it plays are often overlooked. Although soil is a renewable resource, it is often depleted through erosion and degradation faster than it can be replenished through natural processes. It can take thousands of years to form a few centimetres of soil, yet global erosion amounts to approximately 3.4 tonnes per person per year. This amounts to tens of *billions* of tonnes of soil per year, roughly equivalent to an area the size of all of Nova Scotia. Thus, fertile soil can be considered a *non-renewable* in human time scales.

FIGURE 1: *Soil erosion by water flow in an agricultural field.* **(Photo: Wikimedia)**

Soil deterioration occurs not only through erosion (Fig. 3), but also via a host of other processes. While over 35% of the Earth's ice-free land area is used for agriculture to feed the global population of over 7 billion people, this has not been without cost. The process of clearing the natural vegetation has led to increased erosion and losses in soil organic carbon, depletion of vital nutrients, waterlogging, acidification, salinization, and reduced soil biodiversity. The Food and Agriculture Organization (FAO) of the United Nations estimates that approximately one third of the world's soils are moderately to highly degraded (http://www.fao.org/globalsoilpartnership/en/).

The process of urbanization to house the world's growing population also leads to negative effects. Construction and the paving over of the soil surface with concrete and asphalt results in surface sealing and compaction (Fig. 4). Industrial processes may lead to soil contamination with heavy metals and other chemical contaminants.

FIGURE 2: *Lower Manhattan, New York. Urbanization, including buildings and highways, seals the soil surface from natural processes and removes it from agricultural production.* **(Photo: Wikimedia)**

FIGURE 3: *A riparian buffer—bands of natural vegetation along a stream course to prevent soil eroded from adjacent fields reaching the stream. Also note the contour plowing of the fields—plowing across the slope rather than straight up and down the slope.* **(Photo: Daryl Dagasse)**

These threats can, however, be reduced through the adoption of sustainable soil management strategies. Erosion can be reduced through the adoption of minimal tillage and use of crop residues to avoid having a bare soil surface susceptible to the effects of wind and water. Contour tillage across soil slopes rather than down them and the incorporation of vegetation buffer strips (riparian buffers) to catch eroded soil before it reaches streams can also help (Fig. 5). Crop residue and other organic matter additions to the soil can also reduce nutrient imbalances and promote healthy soil microbial populations. For any conservation and preservation strategies to be effective, action is required of all levels of stakeholders, ranging from federal governments to individual landowners.

"Civilizations don't disappear overnight. They don't choose to fail. More often they falter and then decline as their soil disappears over generations. Although historians are prone to credit the end of civilizations to discrete events like climate changes, wars, or natural disasters, the effects of soil erosion on ancient societies were profound."

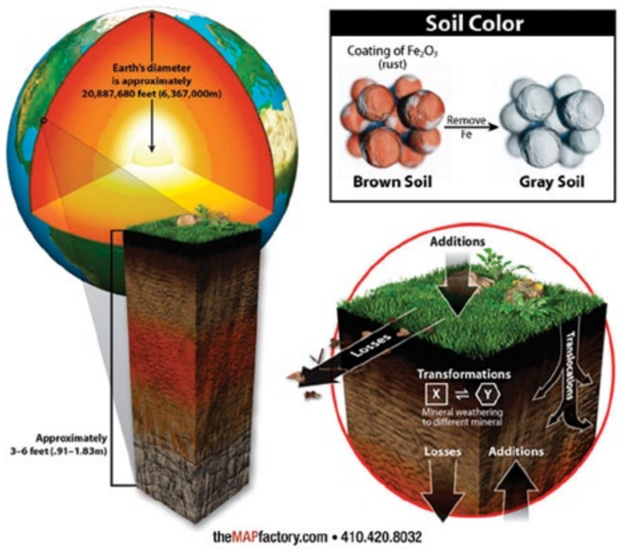
—(From: *Dirt: The Erosion of Civilizations* by David R. Montgomery)

SECTION 2 Characteristics of Soils

Prepared by Lindsey Andronak, Eryne Croquet, Richard Heck, and David Kroetsch

Soil is a renewable resource but it renews itself slower than it is eroded or degraded. The average depth of soil is almost a meter but compared to the diameter of earth (~6.3 million meters), it is a tiny fraction of the earth.

We depend on soil because it allows us to grow food and forests, build roads and highways, make concrete, bricks, and pottery, filter toxins out of water, and many other things. It also provides habitat for worms, spiders, mites, and microbes.



(Source: soils4teachers.org)

A bit about soil science...

Soils are nearly alive because they grow. Their development is called pedogenesis. The process starts at the top of the soil, where organic litter gets incorporated into the inorganic mineral portion of the soil. **Pedogenesis** forms soil horizons—usually these are easy to see because they have different colours. Soil horizons are often parallel to the soil surface and are distinguished
by some of the soil properties we describe in a soil pit, including soil texture and soil colour.

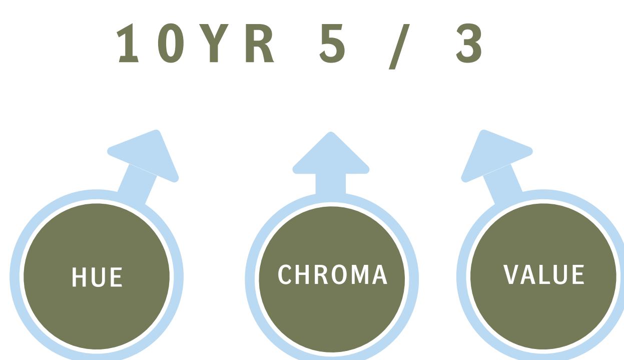
Soil scientists use the horizons to determine how the soil formed. Since soils aggregate all the environmental factors, they are good recorders of recent past environmental conditions in a location. Essentially, the type of horizons a soil forms depends on the environmental soil-forming factors. There are five main soil forming factors: climate, topography, parent material, time, and organisms. These five factors influence pedogenesis to form certain kinds of soil horizons.

Soil Colour

The first impression we have when looking at bare earth or soil is of colour. Bright colours especially, catch our eye. Soil colours are made as the soil forms on recently-deposited sediments. The colours develop from chemical weathering of parent material minerals. For example, red colours in soil are associated with iron oxidation, or rusting.

Munsell Colour System: How We Describe Soil Colours

Red, brown, yellow, yellowish-red, grayish-brown, and pale red are all good descriptive colours of soil, but not very exact. Soil scientists use a book of colour chips that follow the Munsell System of Colour Notation. The Munsell System allows for direct comparison of soils anywhere in the world. With a soil colour book with Munsell notations, a science student or teacher can visually connect soil colours with natural environments of the area, and students can learn to read and record the colour, scientifically. Soil colour by Munsell notation is one of many standard methods used to describe soils for soil surveys. Munsell colour notations can be used to define an archeological site or to make comparisons in a criminal investigation.The system has three components: hue (a specific colour), value (lightness and darkness), and chroma (colour intensity) that are arranged in books of colour chips. The soil colour is described using the Munsell notation that lists the **hue**, **chroma**, and **value**, for example 10YR 5/3. The soil sample is compared to the chips to find a visual match and assigned the corresponding Munsell notation.



Soil Composition and Colour

Soil colour and other properties including texture, structure, and consistency are used to distinguish and identify soil horizons (layers) and to group soils according to the soil classification system.

Colour development and distribution of colour within a soil profile are part of pedogenesis (soil formation). As sediment containing iron or manganese is weathered, the elements oxidize. Iron forms small crystals with a yellow or red colour, organic matter decomposes into black humus, and manganese forms black mineral deposits. These pigments paint the soil. Colour is also affected by the environment: aerobic environments produce sweeping vistas of uniform or subtly changing colour, and anaerobic (oxygen lacking) wet environments disrupt colour flow with complex, often intriguing patterns and points of accent. With depth below the soil surface, colours usually become lighter, yellower, or redder.

Interpreting Soil Colour

Colour can be used as a clue to mineral content of a soil and how a soil forms. Iron minerals, by far, provide the most and the greatest variety of pigments in earth and soil.

Relatively large crystals of goethite give the ubiquitous yellow pigment of aerobic soils. Smaller goethite crystals produce shades of brown. **Hematite** (an iron-based mineral; Greek for blood-like) adds rich red tints. Large hematite crystals give a purplish-red colour to geologic sediments that, in a soil, may be inherited from the geologic parent material. In general, **goethite** (a distinct iron-based mineral) soil colours occur more frequently in temperate climates, and hematite colours are more prevalent in hot deserts and tropical climates.

Colour or lack of colour can tell us something about the environment. Anaerobic environments occur when a soil has a high water table or water settles above an impermeable layer. In many soils, the water table rises in the rainy season. When standing water covers soil, any oxygen in the water is used rapidly, and then the aerobic bacteria go dormant. Anaerobic bacteria use ferric iron (Fe^{3+}) in goethite and hematite as an electron acceptor in their metabolism. In the process, iron is reduced to colourless, water-soluble ferrous iron (Fe^{2+}), which is returned to the soil. Other anaerobic bacteria use manganese (Mn^{4+}) as an electron acceptor, which is reduced to colourless, soluble Mn^{2+}. The loss of pigment leaves gray colours of the underlying mineral. If water stays high for long periods, the entire zone turns gray.

When the water table edges down in the dry season, oxygen re-enters the soil. Soluble iron oxidizes into characteristic orange coloured mottles of **lepidocrocite** (same mineral formula as goethite but different crystal structure) on cracks in the soil. If the soil aerates rapidly, bright red mottles of **ferrihydrite** form in pores and on cracks. Usually ferrihydrite is not stable and, in time, alters to lepidocrocite.

Soil adds beauty to our landscapes. These colours blend with vegetation, sky, and water. For art students and others who may be interested in creating a natural look to their artwork, try to incorporate finely ground coloured soils as pigments into your work.

Influence of Organic Matter on Soil Colour

Soil has living organisms and dead organic matter (leaves, needles, pine cones, dead animals), which decomposes into black humus. In grassland (prairie) soils, the dark colour permeates through the surface layers bringing with it nutrients and high fertility. Deeper in the soil, the organic pigment coats surfaces of soil, making them darker than the colour inside. Humus colour decreases with depth and iron pigments become more apparent.

In forested areas, organic matter accumulates on top of the soil. Water-soluble carbon moves down through the soil and scavenges bits of humus and iron that accumulate below in black, humic bands over reddish iron bands. Often, a white layer, mostly quartz occurs between organic matter on the surface where pigments were removed.

Organic matter plays an indirect, but crucial role in the removal of iron and manganese pigments in wet soils. All bacteria, including those that reduce iron and manganese, must have a food source. Therefore, anaerobic bacteria thrive in concentrations of organic matter, particularly in dead roots. Here, concentrations of gray mottles develop.

Soil colour is a study of various chemical processes acting on soil. These processes include the weathering of geologic material, the chemistry of oxidation-reduction actions upon the various minerals of soil, especially iron and manganese, and the biochemistry of the decomposition of organic matter. Other aspects of Earth science such as climate, physical geography, and geology all influence the rates and conditions under which these chemical reactions occur.

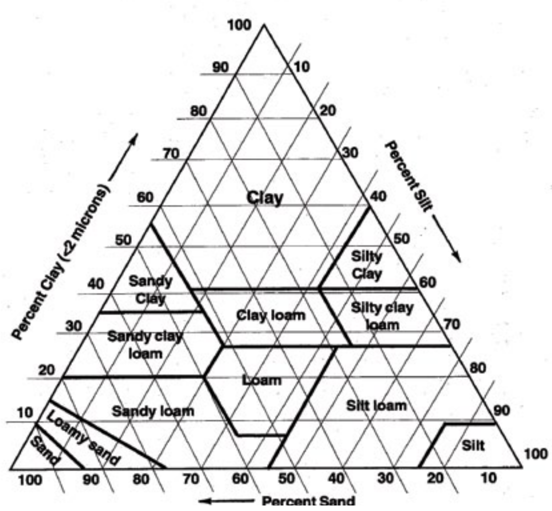
Adapted from: Lynn, W.C. and Pearson, M.J., The Colour of Soil, The Science Teacher, May 2000.

Soil Texture

Soil texture is an important characteristic of soil because it determines the surface area of the soil and that governs the nutrient and water holding capacity of soil. Determining soil texture is important for determining the size of void spaces in soil which is important when considering water movement through soil and risk of compaction and erosion.

Mineral soils are composed of soil particles that differ in size. Anything smaller than 2 mm in diameter is considered to be soil. Larger particles are considered coarse fragments. There are three soil particle size classes: sand, silt, and clay. Sand is the largest diameter soil particle 0.05 mm to 2.0 mm, silt is 0.002 to 0.05 mm and clay is less than 0.002 mm.

We describe soil texture as the approximate amount of each particle size class in the soil sample. There are 16 textural soil classes that we use to describe the texture. The soil texture triangle shows all the soil texture classes and the amount of each particle size for each. In this figure, C is clay, Si is silt, S is sand, and L is loam. So SiCL means silty clay loam and LS means loamy sand. HC is heavy clay.



(Source: http://sis.agr.gc.ca/cansis/glossary/t/)

Student Activities

The following two exercises will ask you to describe some soil characteristics that soil scientists use to determine the best use for a soil. First, we will describe soil colour using the Munsell soil colour book and then we will determine the soil texture of a variety of soil samples.

Activity 1: Determine Soil Colour

We will determine the colour of the soil in the soil pit using the Munsell soil colour book.

Procedure

1. Become familiar with the soil colour book. Each hue is one page of the book. The colour chips on each page are arranged like a table with different values on the x-axis and different chromas on the y-axis.
2. Practice naming the different colours in Munsell notation and with the soil colour names.
3. Collect a small sample of soil in your hand. Discard any rocks, roots, and debris.
4. Compare your sample to the chips in the book. What colour is your sample? Why?
5. Wet your sample and repeat the colour exercise. Is the colour different? Why or why not?

Activity 2: Determine Soil Texture

We will use a technique called hand texturing to determine the soil textural classes of the soil. Soil hand texturing requires manipulating a small sample of soil in your hand with a bit of water, then using a key to determine what class it is in.

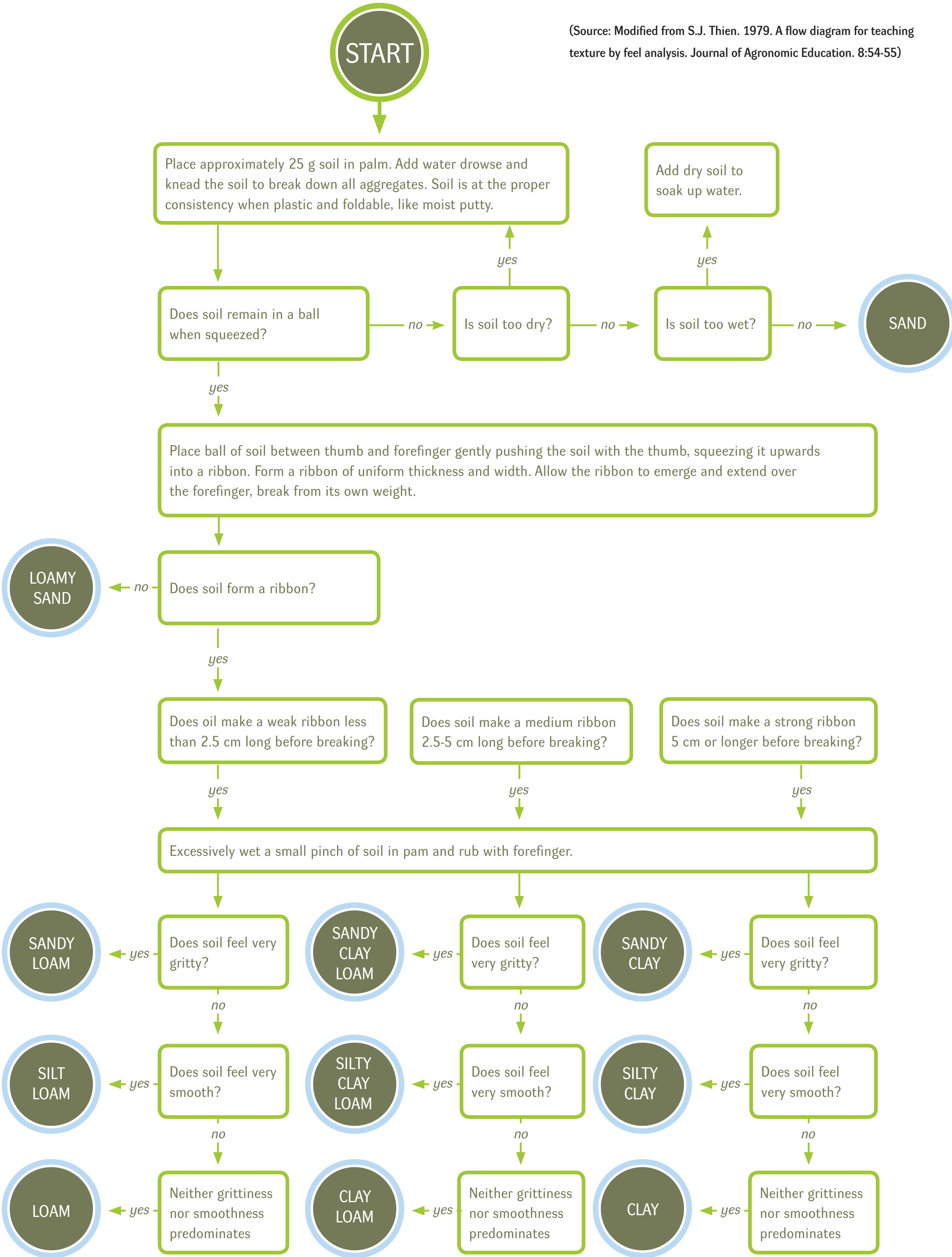
Procedure

1. Collect a small sample of soil in your hand. Discard any rocks, roots, and debris.
2. Spray your sample of water and gently massage the water into the soil.
3. Follow the steps in the soil texture key on the following page to determine the textural class of each soil horizon. Is there a different soil texture for each horizon? Why or why not?

Materials Needed

Soil pit or samples
Munsell soil colour book
Soil texture triangle or key

(Source: Modified from S.J. Thien. 1979. A flow diagram for teaching texture by feel analysis. Journal of Agronomic Education. 8:54-55)



SECTION 3 Soil Classification in Canada

Prepared by Eryne Croquet and David Kroetsch

Canadian soils are classified according to the criteria in the Canadian System of Soil Classification 3rd Ed. The system classifies the soil based largely on morphological characteristics (soil colour, texture, horizonation, etc.) that are described in pedons but it also uses some chemical characteristics.

The system is hierarchical with each level a refinement of the preceding one. The classes are Order, Great Group, Subgroup, Family, and Series. The broadest class is the soil order. It separates soil into classes based on the kind and degree of soil-forming processes that reflect the major differences in pedogenesis. We recognize 10 soil orders in Canada.

The following segments provide a brief description of each order and describe the classification criteria for each.

Brunisols

Brunisols form under forest vegetation. Their morphologic characteristic is having a brownish-coloured Bm horizon (Brun = Brown). They have greater soil development than Regosols but lack the degree of horizon development associated with other orders.

The Bm horizon may have some or all of the following characteristics:

- Stronger chroma and redder hue than the underlying material
- Partial or complete removal of carbonates
- Slight illuviation based on the occurrence of an overlying Ae horizon
- A structural change compared to unaltered parent material.

Brunisols have a Bm, Bfj< thin Bf, or Btj horizon at least 5 cm thick. They lack a solonetzic or podzolic B horizon, a Bt horizon, gleying, thick organic horizons, permafrost or cryoturbation, or a chernozemic A horizon.

Typical horizon sequences for Brunisolic soils is: Ah, Bm, C or Ck.

There are four great groups, distinguished by the kind and sequence of horizons (see table).

Great Group

Property	Melanic	Eutric	Sombric	Dystric
Horizon	Thick Ah or Ap (≥10 cm)	No (or thin) Ah or Ap (< 10 cm)	Thick Ah or Ap (≥10 cm)	No (or thin) Ah or Ap (< 10 cm)
pH	≥5.5	5.5	<5.5	<5.5
Ap colour value	Moist <4	Moist ≥4	Moist <4	Moist ≥4

Brunisolic soil exposed in a roadcut in the Kootenay region of southeast BC. The vegetation was a mid-elevation coniferous forest with a grassy understory. Note the browner colours near the soil surface and the large coarse fragment component. The parent material was till. This soil is most likely a Melanic Brunisol because the parent material was derived from limestone bedrock.

(Photo: Eryne Croquet)

Chernozem

Chernozems are grassland soils that have a characteristic darkening of the surface horizons caused by accumulation of organic matter from the decomposition of grasses and forbs. They are primarily located in the prairie region of Canada, although there are limited occurrences in valley bottoms in BC's Cordilleran Region.

Chernozemic soils must have a diagnostic chernozemic A horizon. The chernozemic A horizon has the following specific characteristics:

- Ah or Ap horizon at least 10 cm thick
- Colour value darker than 5.5 dry or 3.5 moist and a moist chroma less than 3.5
- At least one Munsell colour unit darker than the 1C horizon
- 1% to 17% organic C and C:N less than 17
- Lacks massive structure and hard consistence and single grained structure when dry
- Base saturation more than 80% and Ca is dominant exchangeable cation
- Mean annual soil temperature ≥ 0 °C
- Soil moisture subclass drier than humid
- May have Ae, Bm, or Bt horizon

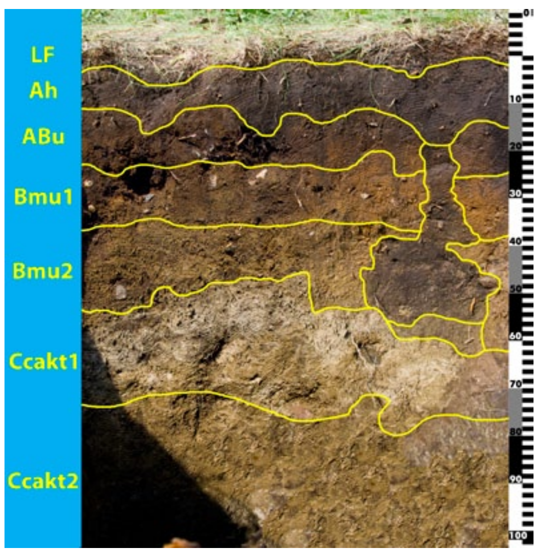
A typical horizon sequences for a Chernozem is Ah, Bm, Ck

There are four great groups within the Chernozemic order (Brown, Dark Brown, Black, and Dark Gray) that are separated based on these properties:

Great Group

Property	Brown	Dark Brown	Black	Dark Gray
Horizon	Ah or Ap	Ah or Ap	Ah or Ap	Ah or Ap
Dry colour value	4.5–5.5	3.5–4.5	<3.5	3.5–4.5 or 3.5–5.0 for Ap
Dry chroma	Usually >1.5	Usually >1.5	Usually ≤ 1.5	Usually ≤ 1.5
Climate	Subarid to semiarid	Semiarid	Subhumid	Subhumid

See http://web.unbc.ca/~soc/ggroup/obrc.html for photos.



Chernozemic soil. Note the surface horizon's dark colour as a result of the decomposition of organic matter. **(Photo: Kent Watson, Thompson Rivers University)**

Cryosol

Cryosols are the frozen soils from the areas of Canada where there is permafrost. They are common north of the treeline and in the alpine areas. They are associated with cryoturbation and permafrost and interesting landforms such as patterned ground, sorted and nonsorted nets, hummocks, etc. Cryoturbation, or frost churning, is when soil horizons become mixed by the action of freezing and thawing of soil material and water in the soil.

They form in mineral or organic parent materials that have permafrost within 1 m of the ground surface or within 2 m if the pedon has been strongly cryoturbated. The mean annual soil temperature is ≤0°C.

Cryosol horizon sequence vary depending on the parent material but can be Om, Omz, Cz or Ah, Bm, C, Cz.

There are three great groups: Turbic, Static, and Organic. They are differentiated based on the degree of cryoturbation and whether the parent material is organic or mineral.

Great Group

Property	Turbic	Static	Organic
Parent Material	Mineral	Mineral	Organic
Cryoturbation	Marked, patterned ground	None	None
Permafrost	Within 2 m of surface	Within 1 m of surface	Within 1 m of surface

See http://soilweb.landfood.ubc.ca/monoliths/cryosol for photos

Gleysol

Gleysols are recognized by mottling and gleying associated with periodic or sustained reducing conditions during pedogenesis. Reducing conditions occur when the soil is saturated from a high groundwater table, temporary accumulation of water above an impermeable layer, or both.

Gleysols must have a horizon at least 10 cm thick, that occurs within 50 cm of the soil surface with:

- For all but red (hues of 5YR or redder)
  - Dominant chromas of 1 or less or hues bluer than 10Y with or without mottles
  - Dominant chromas of 2 or less in hues of 10YR or 7.5YR accompanied by prominent mottles 1 mm or larger in cross section, occupying at least 2% of the soil layer
  - Dominant chromas of 3 or less in hues yellower than 10YR with prominent mottles 1 mm or larger on 2% of the soil layer.
- For red soils (5YR or redder)
  - Distinct or prominent mottles at least 1 mm in diameter on 2% of the soil layer

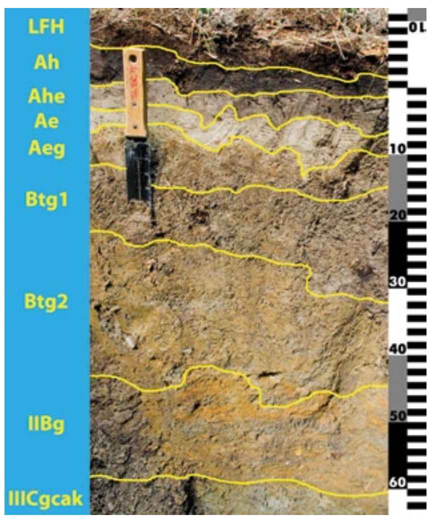
Mottles are redoximorphic features of the soil that appear as spots or streaks of a different colour, usually reddish, yellowish, or whitish. They are described in terms of size, distribution, and the colour difference between the mottle and the unmottled part of the soil.

A common horizon sequence is Ah, Btg, Cg.

There are three gleysolic great groups that divide the order based on the thickness of the A horizon and the type of B horizon.

Great Group

Property	Luvic	Humic	Gleysol
A horizon	Ahe or Aeg	Ah at least 10 cm thick	No Ah or and Ah < 10 cm thick
B horizon	Btg	No Bt	No Bt



Luvic Gleysol. Note the orange-coloured mottles at the base of the pit and the accumulation of finer-textured particles in the Btg horizon near the middle of the profile. **(Photo: Kent Watson, Thompson Rivers University)**

Luvisol

Luvisols are distinguished by an illuvial Bt horizon that has accumulated silicate clays from upper horizons. The soils form in well to imperfectly drained sites with sandy loam to clay textured parent materials under forest vegetation. They are widespread across Canada.

Soils must have an eluvial and illuvial sequence of horizons (Ae and Bt) in order to be classified as Luvisols. The requirements for a Bt horizon are:

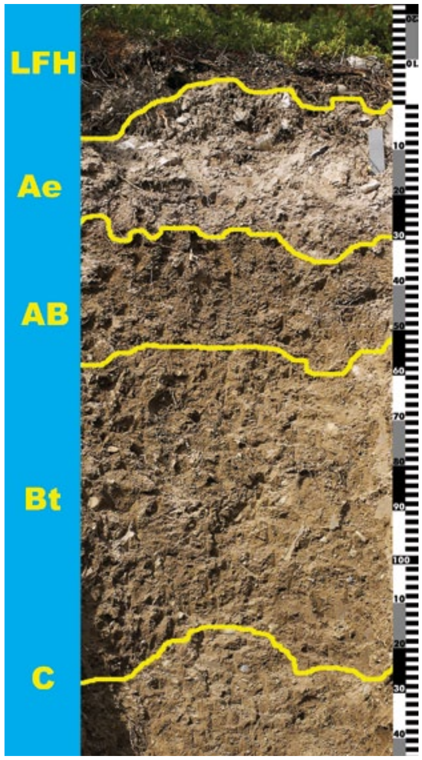
- Clay skins, indicating clay translocation
- >5 cm thick
- Have an Ah, Ahe, or Ap horizon that:
    - Is not a chernozemic A horizon
    - The darker A horizon is underlain by a light coloured Ae horizon that extends up to 15 cm from the surface
    - The dark A horizon shows evidence of eluviation and is underlain by an Ae horizon at least 5 cm thick
    - If the soil moisture regime is humid or wetter, the A horizon can be any kind.

Luvisols form when clay suspended in the soil solution moves downward through the soil profile to deposit at a depth where downward flow ceases. The zone of maximum clay accumulation occurs above a Ck or C horizon. The alluvial surface horizons often have platy structure. A typical horizon sequence if Ah, Ae, Bt, C.

There are two Luvisolic great groups that are distinguished based on the character of the A horizon and soil temperature.

Great Group

Property	Gray Brown	Gray
A horizon	Forest mull Ah	May or may not have an Ah horizon
B horizon	Eluvial and Bt horizons	Eluvial and Bt horizons
Mean annual soil temperature	≥8 °C	<8 °C



A Vertic Gray Luvisol that formed on a glaciolacustrine deposit. **(Photo: Kent Watson, Thompson Rivers University)**

Organic

Organic soils are notable because they form in organic sediments. They include peat, muck, bog, and fen soils. They are often saturated and have poor to very poor drainage. They occur in many parts of Canada, in particular local depressions. The Folisol great group of Organic soils is unique in that it forms in upland (folic) organic materials in forests. Instead of experience saturation due to landscape position and poor drainage, they are saturated by precipitation and snowmelt. These soils are uncommon and are found in the temperate rainforests on the west coast of British Columbia.

Organic soil pedons are described differently than mineral soils. The profile is divided into three tiers (0 to 40 cm, 40 to 120 cm, and > 120 cm).

Organic soils must contain more than 17% organic C (30% or more organic matter) by weight, and must meet the following criteria:

- For organic materials that are commonly saturated (mosses, sedges, hydrophytic vegetation)
  - For fibric material at the surface, the organic material must extend to at least 60 cm
  - For mesic or humic surface material, the organic material must extent to at least 40 cm
  - If a lithic contact occurs within 40 cm of the surface, the organic horizon must be at least 10 cm thick
  - Mineral horizons can occur in organic soils, provided they are underlain by at least 40 cm of organics
- For folic materials (L-F-H)
  - At least 40 cm of folic material over mineral soil or peaty material
  - More than 10 cm of folic material if lying over bedrock or fragmental materials like talus

A horizon sequence for a saturated organic soil is Of, Om, C. Folisols are typically F, H, O.

There are four Organic great groups that are distinguished by the degree of decomposition of the organic parent material and the content of the middle tier.

Great Group

	Hydrophytic Vegetation			Upland Organic Material
Property	**Fibric**	**Mesic**	**Humic**	**Folic**
Middle tier composition	Fibric	Mesic	Humic	Folic materials, rarely saturated with water

Terric Mesisol from the Fraser River floodplain near Chilliwack. Note the saturated conditions, the prominent gleyed mineral material at the base of the pit and the thick organic material extending to ~80 cm. **(Photo: Eryne Croquet)**

Podzol

Podzolic soils are forest soils that form in medium to coarse textured parent materials in cool to very cold humid to perhumid climates. They have a podzolic B horizon, a Bf horizon enriched with amorphous material composed of organic material, Al, and Fe. They often have a white Ae horizon that appears similar to volcanic ash, which explains the name Podzol which is Russian for "under ash".

To be classified as Podzols, soils must have a diagnostic podzolic B horizon that meets morphologic and chemical criteria.

Morphological criteria of the podzolic B horizon

- ≥10 cm thick
- Black or the hue is 7.5 YR or redder or 10YR near the upper boundary and becoming yellower with depth
- Chroma is >3 and value ≤3
- Brown or black coatings on mineral grains
- Silty feel when rubbed wet unless soil is cemented
- Texture is coarser than clay
- Lacks a Bt horizon or has a Bt horizon deeper than 50 cm from the mineral soil surface.

Chemical criteria for the podzolic B horizon

- Bh horizon > 10 cm with colour value and chroma ≤3 that has more than 1% organic C, less than 0.3% pyrophosphate-extractable Fe (Fep), and has an organic C to Fep ratio of 20 or more.

OR

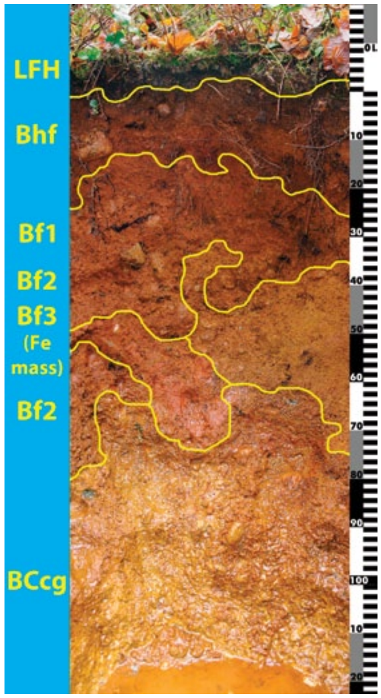
- Bf or Bhf at least 10 cm thick with ≥0.5% organic C, ratio of Fep+Al to clay >0.05, ratio of organic C to Fep <20 or Fep at least 0.3% or either colour value or chroma >3

A horizon sequence for a podzolic soil is Ae, Bf, C or Ae, Bfc, C.

There are three podzolic great groups that are separated based on the organic C content abd the organic C to Fep ratio of the podzolic B horizon.

Great Group

Property	Humic	Ferro-Humic	Humo-Ferric
B horizon	Bh, >10 cm thick	Bhf, >10 cm thick	Bf or thin Bhf + Bf, >10 cm thick
Organic C	>1%	>5%	0.5 – 5%
Pyrophosphate Fe	<0.3%	>0.3%	≥0.3%
Organic C: Fep	≥20	<20	<20
Pyrophosphate Al + Fe	n/a	≥0.6% (0.4% for sands)	≥0.6% (0.4% for sands)



Ferro-Humic Podzol. Note the red Bf horizon from 10 cm to 50 cm showing the accumulation of iron and aluminum.

(Photo: Kent Watson, Thompson Rivers University)

Regosol

Regosols are the weakly-developed soils in Canada that lack a recognizable B horizon. There are several reasons that explain the lack of development: young parent materials, unstable landscapes, resistant parent material mineralogy, cold and dry climate conditions, etc.

They can be recognized in the field by the lack of any type of B horizon.

A common horizon sequence in a Regosolic soil is Ah, C.

There are two great groups that are differentiated based on the presence or absence of a well-developed Ah or Ap horizon.

Great Group

Property	Regosol	Humic
Ah or Ap	< 10 cm	≥ 10 cm
Bm	Absent or < 5 cm thick	Absent or < 5 cm thick

Solonetzic

Solonetzic soils develop from saline parent materials and for characteristic prismatic or columnar structure in the solonetzic B horizon. They are most common in the semiarid to subhumid Interior Plains region of Canada.

They form when salts leach from the surface soil horizons to the B horizon. Further leaching depletes the alkali cations in the A horizon so it becomes acidic and forms platy structure. The B horizon, now enriched in salts, develops darkly stained, fused, intact columnar peds. The upper portion of the B horizon will break down as the exchangeable sodium moves down the profile. With continued solodization, the salt and lime accumulations move from the B to the C horizon. Solodization is arrested where saline groundwater is within the capillary reach of the solum and resalinization occurs.

Solonetzic soils must have a solonetzic B horizon (Bn or Bnt). It has columnar or prismatic structure, hard to extremely hard dry consistence, and has a ratio of exchangeable Ca to Na of 10 or less.

Solonetzic soils may have a horizon sequence of Ah, Bn, Csk.

There are four solonetzic great groups that are divided based on the characteristics of the Ae horizon, the breakdown in the upper part of the B horizon, and the occurrence of vertic features.

Great Group

<table>
<tr><th>Property</th><th>Solonetz</th><th>Solodized Solonetz</th><th colspan="2">Solod</th><th>Vertic Solonetz</th></tr>
<tr><td>Ae Horizon</td><td>No continuous Ae ≥ 2 cm thick</td><td>Ae ≥ 2 cm thick</td><td colspan="2">Ae ≥ 2 cm thick</td><td rowspan="2">Any solonetz features</td></tr>
<tr><td>B Horizon</td><td colspan="2">n/a</td><td>Intact, columnar Bn or Bnt</td><td>Distinct AB or BA (disintegrating Bnt</td></tr>
<tr><td>Vertic features</td><td colspan="2">n/a</td><td>n/a</td><td>n/a</td><td>Slickenside</td></tr>
</table>

See http://web.unbc.ca/~soc/ggroup/bss.html for photos.

Orthic Humic Regosolic soil formed from a ~4000 year old landslide deposit from Mt. Cheam in the Fraser Valley of BC. The soil lacks development in the B horizon but exhibits weak development in the upper horizons. **(Photo: Eryne Croquet)**

Vertisol

Vertisols form in parent materials with ≥60% clay that have shrink-swell characteristics. They have cracking, argillipedoturbation, and mass movement (i.e., slickensides). Shrinking and swelling clays expand or contract as water is stored or removed from between the silicate layers in the mineral structure of the soil. As the soil shrinks, the soil cracks and material from upper horizons falls into the cracks. When the soil swells, the particles slide past one another, forming slickensides. The shrinking and swelling behaviour in Vertisolic soils is sufficient alter horizons formed by other processes or prevent their formation.

Vertisolic soils must have both a slickenside and a vertic horizon. A slickenside horizon (ss) has recognizable slickensides and vertic horizons have irregular shaped, randomly oriented, intrusions of displaced materials within the solum and vertical cracks containing sloughed-in materials.

An Orthic Vertisol may have the following horizons: Ah, Bv, Bss, Ckss

There are two Vertisolic great groups that have been sorted based on the colour of the A horizon and the amount and nature of organic matter incorporated into the soil.

Great Group

Property	Vertisol	Humic
Colour value of A horizon	≥ 3.5 (dry)	< 3.5 (dry)
Chroma of A horizon	Usually >1.5 (dry)	Usually ≤1.5 (dry)
A horizon	Not easily distinguished from rest of solum	Easily distinguished from rest of solum
Ah horizon	< 10 cm thick	≥ 10 cm thick

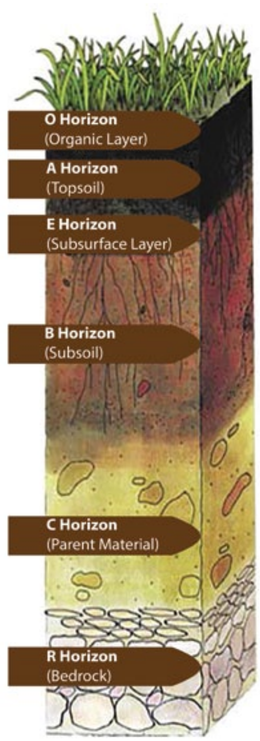
http://soilweb.landfood.ubc.ca/monoliths/vertosol for photos.

UNITED STATES VS. CANADIAN SOIL CLASSIFICATION SYSTEMS

Horizonation

As shown in Figures 1 and 2, the horizonation in soil profiles are almost the same in both systems, with one major difference. The U.S. system includes an E, or eluviated, horizon. The main feature of this horizon is loss of clay, Fe and Al oxides, or both, leaving a combination of sand and silt particles of quartz (or other resistant material). If these characteristics are found in a Canadian profile, the horizon will be described as Ae, with the e being a suffix (or description) for the A horizon.

FIGURE 1. *A typical soil horizon diagram in the U.S. classification system. The Canadian classification would be missing the E (subsurface) Horizon, which, if applicable, would be considered an Ae Horizon* **(Photo: Wikimedia)**



Correlation of Soil Orders

It is important to note that these are **general** equivalents, as characteristic features differ for each order. For more detailed information see The Canadian System of Soil Classification and The USDA Soil Taxonomy.

U.S Soil Order	Defining Characteristic	Canadian Soil Order
Entisol	Limited development, mostly derived from parent material	Regosol
Vertisol	High clay content, shrinking and swelling, formation of large cracks	Vertisol
Inceptisol	Moderate development of horizons	Brunisol
Ardisol	Soils from arid regions, limited change from parent material	some Solonetz
Mollisol	Grassland soils, high in organic matter	Chernozem
Spodosol	Forest soils, illuvial horizons with organic matter, Fe and Al oxides	Podzol
Alfisol	Forest soils, illuvial horizons with clays	Luvisol
Ultisol	Similar to Alfisol but with low degree of base saturation	n/a
Oxisol	Highly weathered tropical soil	n/a
Histosol	Thick organic layer; peat or wetland soils	Organic soils
Gelisol	Soils with permafrost	Crysol
Aqu-suborder[1]	Wet from prolonged water saturation, gleying, mottling	Gleysol

[1]Not a soil order

SECTION 4 Soils, Land Use and Invasive Species

Prepared by Lindsey Andronak, Paul Hazlett, Emma Holmes and Alison Murata

When you think of invasive species, you likely think of plants and animals. Purple loosestrife, zebra mussels and the fungus that causes Dutch Elm Disease. Do soils have invasive species? Does land use affect invasive species?

An **invasive species** is a non-native plant or animal whose introduction causes or is likely to cause economic harm, environmental harm, or harm to human health. The term "invasive" is used for the most aggressive species. These species grow and reproduce rapidly, causing major disturbance to the areas in which they are present.

Invasive Earthworms in North America

Earthworms (Fig. 1) are invertebrates found in the class *Oligochaeta*. Worldwide, there are approximately 6,000 species; however, only about 150 species are widely distributed. They are commonly known for their benefits to soil, especially agricultural and garden soils. These benefits include:

- Transforming organic matter into humus. Humus contains nutrients in a more plant available form, thereby increasing soil fertility. Earthworms also transport these nutrients further down the soil profile, making them more accessible to roots.
- Creating burrows. Burrows increase both soil aeration and drainage.

FIGURE 4: *Lumbricus terrestris, also known as a nightcrawler* ***(Photo: Wikipedia)***

Questions Worth Investigating

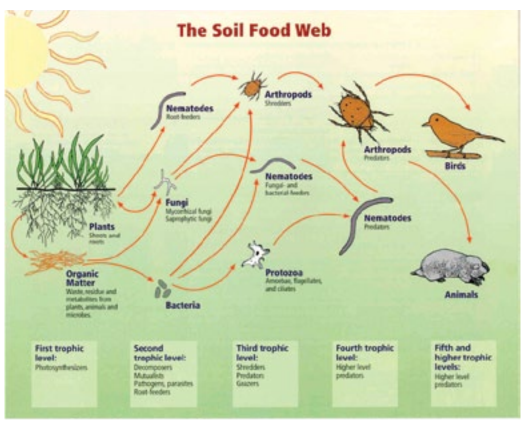
We have just listed a few benefits of earthworms and with a little research, you could likely find others. Read the articles *Soil and the Forest Floor* (Great Lakes Worm Watch, Natural Resources Research Institute) and *Earthworm Invaders Have Huge Implications for Forest Health* (Soil Horizons July 2015) found in Appendix 1. After reading the articles, answer the following questions:

1. How does organic matter cycling, particularly plant organic matter, differ among forest soils, grassland soils and agricultural soils?
2. Why are earthworms considered to be invasive in forest ecosystems?
3. What effects do earthworms have on forest ecosystems and why are these a concern?
4. How is land use increasing the spread of earthworms?
5. How can we reduce the impacts of earthworms in forest soils?

Soil Borne Crop Pests

Nematodes and the Soil Food Web

Adapted from a lecture with Dr. Elaine Ingham (and the American Phytopathological Society)



An incredible diversity of organisms make up the soil food web. They range in size from the tiniest one-celled bacteria, algae, fungi, and protozoa, to the more complex nematodes and micro-arthropods, to the visible earthworms, insects, small vertebrates, and plants.

The organisms of the food web are not uniformly distributed through the soil. Each species and group exists where they can find appropriate space, nutrients, and moisture. They occur wherever organic matter occurs – mostly in the top few centimetres of soil. The rhizopshere, the narrow region of soil directly around roots, is teeming with soil life. This is because roots secrete proteins and sugars that attract bacteria and fungi. Predatory organisms, such as protozoa and nematodes are attracted to the rhizopshere because they eat the bacteria, fungi, and sometimes roots.

Nematodes are non-segmented worms typically 50 µm in diameter and 1 mm in length.

Members of the phylum Nematoda (round worms) have been in existence for an estimated one billion years, making them one of the most ancient and diverse types of animals on earth. The few species responsible for plant diseases have received a lot of attention, but far less is known about the majority of the nematode community that plays beneficial roles in soil.

An incredible variety of nematodes function at several trophic levels of the soil food web. Some feed on the plant roots (first trophic level); others are grazers that feed on bacteria and fungi (second trophic level); and some feed on other nematodes (higher trophic-levels). Nematodes need adequate moisture, moderate temperatures, and protection from direct sunlight.

The majority of nematodes are beneficial for the soil ecosystem, and play the very important role of mineralizing, or releasing, nutrients in plant available forms. When nematodes eat bacteria or fungi, ammonium (NH_4^+) is released because bacteria and fungi contain much more nitrogen than the nematodes require. Nematodes are food for higher level predators, including predatory nematodes, soil microarthropods, and soil insects.

However, some nematodes aren't beneficial to humans. Some nematodes feed on plant roots, and often feed on the roots of crops – these plant-parasitic nematodes must be controlled by humans to ensure agricultural productivity. There are several methods commonly used to control plant-parasitic nematodes. These methods can be divided in to three main types: *biological control*, *cultural control* and *chemical control*. Plant nematodes are not typically controlled using just one method mentioned above, but instead they are managed using a combination of methods in an integrated pest management system (IPMS).

Biological control: It is possible for plant breeders to cross natural nematode resistance genes into cultivated plant species to improve their resistance to nematodes. The benefit of this method is that it is a very inexpensive way for growers to control their nematode problems. The main disadvantage is that it takes years to screen for resistant plant varieties and more time to breed resistance traits into commercial varieties. Other biological control methods use natural predators or pathogens of nematodes. While biological control agents kill nematodes in controlled laboratory settings, implementation of biological control methods in the field is not done due to the expense and difficulty of growing large amounts of nematode pathogens. However, if some of the difficulties associated with growing nematode pathogens can be overcome, this may be a promising method of nematode control in the future.

Cultural Control: Crop rotation with a non-host plant is a very effective method to limit nematode growth. Typically, a cropping system is devised that selects plants that nematodes can and cannot grow on. These plants are grown in alternate years and the problematic nematode population decreases dramatically, below damage threshold levels, in the years that the non-host is grown. This can be an effective method if a producer has the choice of several different crops that can be grown and if the problematic nematode does not have a broad host range or survive in the soil for long periods of time.

Chemical Control: For the past 75 years nematodes have been controlled using chemical nematicides; inexpensive chemicals that kill nematodes in soil. Soil fumigants became popular because they did not rely on alternative host crops for rotation; they drastically reduced nematode populations in the soil, and were cost effective for most crops. Most fumigant nematicides have been banned by the Environmental Protection Agency (EPA) as environmental toxins with the exception of 1,3 dichloropropene (Telone II), chloropicrin (tear gas), and dazomet (Basamid).

Case Study: Nematode Invasion!

You are an environmental scientist working for a consulting company that specializes in ecosystem approaches to invasive species. You have just been contacted by Joseph Wagamese, a farmer in Eastern Ontario, who has been growing soybean and corn on his 200-acre farm for 35 years.

It is July and Joseph has noticed his soybean crop is stunted and the leaves are yellow. At first he thought the symptoms were due to a nutrient deficiency, but his soil management plan has consistently resulted in high soybean yields in the past. When he dug up a plant he saw the roots were dwarfed, discolored, and appeared to be covered in white cysts. He has never seen this before and is not sure what it is. It has affected 30% of his crop and could result in a big economic loss! He can't afford this, which is why he has enlisted your help.

FIGURE 5: *Joseph's soybean field.* **(Photo: Wikimedia)**

FIGURE: *White cysts on the roots of Joseph's soybean plant.* **(Photo: Wikimedia)**

You know that the white cysts are actually Soybean Cyst Nematodes (*Heterodera glycicres*), which has been slowly spreading across Ontario for the past 20 years.

Meanwhile, Susan Jones, a vegetable farmer in Western Ontario, has also contacted you because 20% of her onion crop is wilting in her fields. She used to grow mixed vegetables with a 4-year crop rotation, but due to the high price for onions, she switched her entire 5-acre plot over to onion production. This is her third year of growing an onion monocrop, and she has noticed that the base of her onion seedlings appear swollen and the leaves appear to be twisted. The outer leaves are dying back from the tips and the neck is spongy in texture.

You recognize the symptoms as being caused by bulb and stem nematode (*Ditylenchus dipsaci*), which has been affecting crops in Ontario since the 1950s.

To get started on assisting Joseph and Susan, you start researching the following questions. You studied invasive ecology in university and luckily, still have your notes!

FIGURE 7: *Onions from Susan's farm.* **(Photo: Wikimedia)**

Questions Worth Investigating

1. What part of the food web do nematodes feed in?
2. What organisms feed upon nematodes? What role do nematodes play in the soil food web?
3. Why is soybean cyst nematode (SCN) a concern for Joseph? What effect does it have on his crops and the financial security of his farming operation?
4. Why is bulb and stem nematode (BSN) a concern for Susan? What effect does it have on her crops and the financial security of her farming operation?
5. Why do you think SCN and BSN are invading Joseph and Susan's farms? What are some of the root causes?
6. What are the biological controls for root-parasitic nematodes?
7. What are the cultural controls for root-parasitic nematodes? How may cultural controls affect the economic stability of Joseph and Susan's farms?
8. What are the chemical controls for root-parasitic nematodes? What would the effect be on beneficial nematodes? What would the effect be on other soil micro-organisms (bacteria, fungi, protozoa)? What would be some of the long-term effects on the ecosystem as a whole?
9. What control or combination of controls would you recommend to Joseph? What control or combination of controls would you recommend to Susan?

Here are some web resources you may also find helpful.

Soybean Disease

Bulb and Stem Nematodes in Onions and Carrots

Introduction to Plant-Parasitic Nematodes

Fungal, Bacterial and Viral Diseases

There are many types of diseases that affect crops. Two kinds, Asian soybean rust and clubroot, are presented in Appendix 2 as Wanted Posters. Select a disease that affects crops from your area and create your own Wanted poster.

Forest Invasive Insects

Defoliation and death of trees by introduced invasive insects is impacting urban areas and forested ecosystems. In cities, trees play an important role in providing windbreaks and shading, controlling water runoff, reducing air pollutants and contributing to overall human health. Damage from these insects has significant economic and social impacts. Removal and replacement of dead trees is a large cost to municipalities and homeowners. In forestry dependent communities, tree death represents a loss of a resource that is used to provide important local jobs and forest products for all of society.

Less obvious are the ecological impacts of invasive insects especially on soil and the ecosystem services that soil provides such as water filtration and nutrient cycling. In many forests a single tree species can dominant the stand composition. These so called *foundation species* not only control forest structure but also soil properties, processes and biotic communities. In fact, many organisms, from the smallest bacteria to the largest mammal have adapted to live under the conditions that developed under the foundation species.

Loss of a foundation species from invasive insects can create large openings or gaps in the forest canopy where temperature and moisture conditions will change. These changes have the potential to modify the plants that grow in the forest, and decomposition and water movement in the soil. Immediately after tree death large branches and entire trees fall to the forest floor providing a pulse of downed woody debris and nutrients. Over time, decreased litter from the foundation species and increased dominance of litter from other tree species changes the food type for soil organisms. Differing chemical composition of leaves from different tree species can be more or less desirable to certain organisms resulting in impacts on entire soil food webs.

While detailed information on the impact to forest soil health by invasive insects is scarce, forest managers are immediately required to determine if action needs to be taken to protect the valuable ecosystem services provided by soil. Allowing other tree species to naturally regenerate in openings left by the dead trees is generally the lowest cost option but may not reduce the effects on soil. More proactive actions could include the strategic removal of some of the susceptible trees before insect infestation to moderate impacts, or the replacement of these trees with other species that could serve the same function in the forest ecosystem. Any actions will need to consider ecological, economic and social considerations.

Case Study: The emerald ash borer in riparian forests

The emerald ash borer (EAB) is an invasive insect originating from Asia that kills ash trees. It was discovered in Detroit, Michigan and Windsor, Ontario in 2002 and since then has been found throughout Ontario and in 24 states in the US. The feeding of the insect larvae in galleries between the tree bark and sapwood results in tree death. It is predicted that EAB will kill most of the ash trees in North America over the next decade. Ash dominated riparian forests are common throughout south-western Ontario.

Riparian areas are the transition zone between land and water in forests and therefore important regulators of aquatic ecosystems. The intimate relationship between soil and stream means that loss of ash in riparian forests can directly affect streams by modifying soil microclimate, nutrient inputs and water filtration by soil. Ash leaf litter is known to provide a nutrient rich food, especially nitrogen, for organisms compared to many other forest litters and therefore loss of ash could reduce nutrient levels and change aquatic communities in associated streams.

Student Activity: EAB Management

You are the forest manager for a conservation authority near Alvinston in south-western Ontario. You have several streams associated with riparian forests in your conservation area that range in ash composition from 10% to 70%. You are on the leading edge of EAB infestation and it is expected that all the ash trees in your area will be dead in 3 years. What forest management activities or combination of activities would you implement to maintain critical riparian habitats? Consider ecological, economic and social factors when developing your management plan. You will need to explain your plan to the directors of your conservation authority and the general public so provide reasons for your approaches.

To assist with your answers:

1. One ash species, blue ash, appears to be less susceptible to EAB, does not occur in large numbers in your area but does occur in similar riparian habitats, and does have nutrient rich litter like other ash species.
2. Other tree species such as elm and hickory occur in some of the riparian forests of your area and has been shown to have leaf litter chemistry similar to ash.
3. Insecticides have been developed to protect ash trees from EAB but the treatments involve single tree injections and are quite costly.

FIGURE 8: *Adult emerald ash borer.* **(Natural Resources Canada)**

FIGURE 9: *Mature emerald ash borer larva.* **(Natural Resources Canada)**

FIGURE 10: *Dead ash trees in riparian forests of south-western Ontario* **(Paul Hazlett, Canadian Forest Service)**

FIGURE 11: *Emerald ash borer galleries in infested riparian trees* **(Paul Hazlett, Canadian Forest Service)**

SECTION 5 Soils, Land Use, and Climate Change

Prepared by Maja Krzic, Katie Neufeld, Matthew Swallow, and Carolyn Wilson

Learning Objectives

This lesson will allow learners to understand:

1. How climate affects soil formation and soil properties,
2. The global carbon (C) cycle and soil's role as a source and sink by being able to describe the storage and transformations of carbon in soil,
3. How different ecosystems and different land uses might have different carbon balances, and
4. How land conversion from native to agricultural land use affects soils' ability to retain carbon.

Climate Change

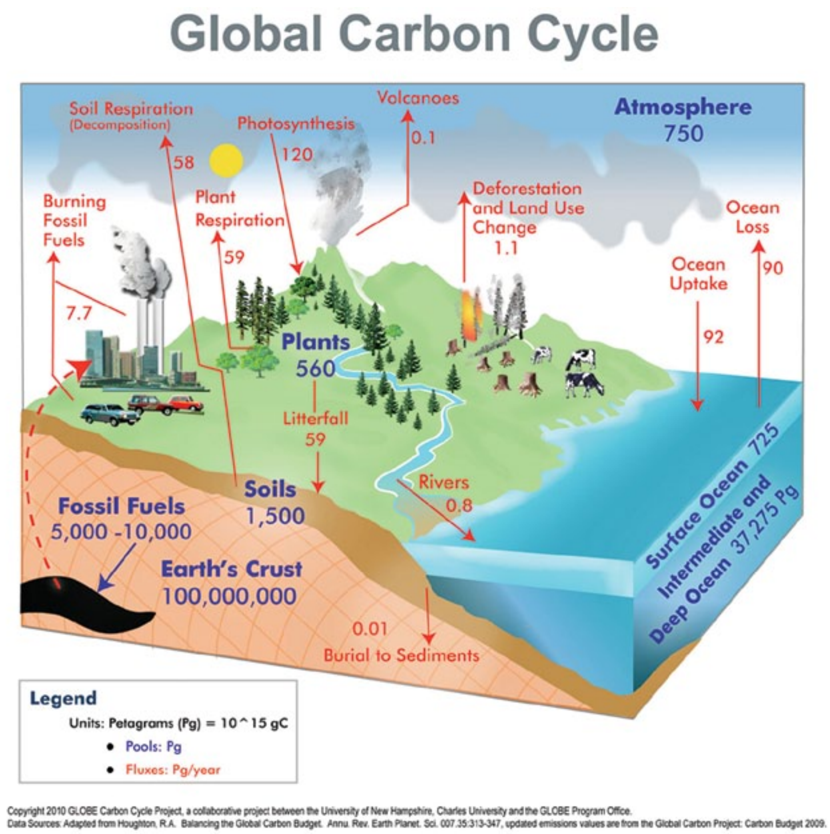
Earth receives solar radiation from the sun and emits infrared radiation from its surface. Molecules in our atmosphere called **greenhouse gases** (carbon dioxide, methane, nitrous oxide, and water vapour) absorb some of the infrared radiation and re-emit it. This **greenhouse effect** makes temperatures warm enough to support earth's living organisms. If the concentration of greenhouse gases in the atmosphere increases, the earth's temperature tends to increase as well. Earth's climate is continually changing. Naturally occurring variations in climate **(climate change)** have occurred throughout history; however, current climate warming has been linked to increased human emissions of **greenhouse gases (**Brinkman and Sombroek 1996**)**.

Soil plays an important role in climate change because it can serve as both a greenhouse gas **source** (when the soil produces more than it stores) and **sink** (when the soil stores more than it emits), especially for carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). These gases are natural by-products of soil microbial processes, including some of the same processes (e.g. respiration and nitrification) that provide plant-available nutrients and contribute to ecosystem stability. However, if the equilibrium of these microbial processes is disrupted by a changing climate, the rate of greenhouse gas emissions could change rapidly.

Global Carbon Cycle

Like all matter, carbon cycles throughout the earth system (Figure 1). To understand how carbon is cycled and how atmospheric CO_2 will change in the future, scientists must carefully study the places in which carbon is stored (**pools**), how long it resides there, and processes that transfer it from one pool to another (**fluxes**). Collectively, all of the major pools and fluxes of carbon on Earth comprise what we refer to as the Global carbon Cycle.

FIGURE 1. *Diagram of the global carbon (C) cycle. C-pool sizes (blue) are in petagrams (Pg) and C-fluxes (red) are in Pg per year.* **(Source: The GLOBE Program)**



Questions Worth Investigating

1. What are the most common greenhouse gases?
2. Explain how greenhouse gases contribute to climate change.
3. What changes would occur for microbial and plant communities in the Arctic if it becomes
   a. much warmer than today
   b. much wetter than today?

Climate: A Major Factor of Soil Formation

Climate, along with parent material, topography, organisms, and time, is one of the five key factors of soil formation (Soils of Canada). Climate greatly influences soil formation through precipitation, temperature, and wind.

Across the globe, soils vary greatly from one climatic zone to another. For example, tropical soils are formed in areas with high temperature and high annual rainfall. These soils are highly **weathered** and have low nutrient content because nutrient ions have **leached** out of the soil profile. The abundant tropical vegetation helps to return some of these nutrients to the soil.

In temperate climates, such as much of Canada, soil formation is relatively slow, as snow cover and cool temperatures in winter slow many weathering processes. In northern Canadian and Arctic regions, soil formation is very restricted and greatly affected by freeze-thaw processes and **permafrost** (Figure 2) conditions. In dry climates, low precipitation and significant evaporation give rise to soils high in soluble salts, such as calcium carbonate or gypsum.

FIGURE 2. *Cracks forming at the edges of a permafrost area.* **(Photo: Wikimedia)**

How Precipitation, Temperature, and Wind Form Soil

Precipitation

Rainwater readily dissolves salts and ionic compounds on the surface of rocks and parent materials. High rainfall amounts and intense weathering can cause nutrients to leach down into the lower horizons of the soil profile. An example of a soil type in which these processes commonly take place is the **Podzol** (Figure 3), often found in eastern Canada and western British Columbia (Soil Classification: Canadian Soil Orders 2008). In these soils, compounds such as soluble organic matter and/or iron and aluminum oxides/hydroxides have moved down the profile, leaving behind grey A horizon and resulting in formation of intensely coloured B horizon(s).

FIGURE 3. *Podzolic soil with grey A horizon and orange colored B horizons.* **(Photo: Wikimedia)**

Water can also result in anaerobic (oxygen free) soil conditions. Without oxygen, many microbes cannot survive and therefore cannot decompose organic matter. Under anaerobic conditions, organic matter accumulates leading to formation of soils of the **Organic** order.

Temperature

Temperature also influences soil formation. Warmer temperatures encourage organic matter decomposition as well as faster chemical reactions, speeding up the weathering process. As organic material is broken down, carbon is released as CO_2 and also incorporated into organic molecules within the bodies of the decomposer organisms. In cold temperatures, decomposition is slowed.

Another example of temperature's impact on soil formation is through the freeze-thaw cycles that physically break up bedrock or sediment. First, liquid water enters crevices in rocks (i.e. parent material). When water freezes, ice may force these cracks to grow and smaller rock fragments may break off (Figure 4).

FIGURE 4. *Rock weathering due to freeze-thaw effect.* **(Photo: Wikimedia)**

Wind

Wind influences soil through erosion and deposition. Wind can also influence the effectiveness of precipitation in the weathering process. For example, strong winds can increase the penetration of rain or snow into crevices in parent rock material.

Soil in a Changing Climate

Climate has a major effect on soil formation. Consider the glaciers that once covered essentially all of Canada some 10-20 thousand years ago. As they receded, these glaciers had a lasting effect on soil and landform through erosion and deposition processes. Currently, Earth is in a period of warming. What kinds of effects will today's changing climate have on soil formation?

It is predicted that climate change will directly affect **soil organic matter** supply, temperatures and **hydrology**. One major change will be the poleward retreat of the permafrost boundary as a result of increased soil temperatures due to warmer climatic conditions. In some areas of Canada, a warming climate will also result in an expansion in growing season, increasing the growth of vegetation and consequently offering protection against soil erosion and runoff. Climate change will also have an indirect effect on soils. These effects will be most obvious in areas with higher temperatures and greater rainfall variability. Some of these effects include increases in plant growth and water-use due to increased atmospheric CO_2, sea-level rise, climate-induced decrease or increase in vegetative cover, and a change in human influence on soils.

The effects of climate change will not be uniform across all ecosystems. In unprotected low-lying coastal areas, extensive flooding by **brackish water** will encourage the gradual establishment of *Rhizophora* mangroves (Figure 5). After several decades, these conditions lead to the formation of anaerobic, acid sulphate soil layers that are prohibitive for growth of most plant species.

FIGURE 5. *Red mangrove in Everglades National Park, Florida.* **(Photo: Wikimedia)**

In boreal climates, a gradual reduction in permafrost is expected to result in nutrient leaching from soil over vast land areas. With anticipated climate change, temperatures high enough for microbial activity would occur for longer periods of time, leading to higher organic matter decomposition. This loss of organic matter would likely not be fully compensated for by higher net photosynthesis and the longer growing period (net primary production). It is also expected that greater extents of soil will see increased periods when the soils are water-saturated (anaerobic) but also sufficiently warm for microbial activity. This will likely result in nutrient leaching and potentially have environmental effects. To protect the world's soils against negative effects of climate change land users should:

- Manage their soils to give them maximum physical resilience through a stable pore system (comprised of large and small pores) by maintaining as much ground cover possible; and
- Use management systems (e.g. crop rotation, soil cover, crop residue management, drainage management, and others) that balance the input and offtake of nutrients, while maintaining soil nutrient levels low enough to minimize losses and high enough to buffer occasional high plant demands.

Questions Worth Investigating

1. Podzolic soils are one of 10 soil orders found in Canada. Using the information found in Section 3: Canadian System of Soil Classification, explain how climate influences the formation of soil horizons in another soil order.
2. Why do colder temperatures cause slower decomposition and weathering?
3. Select an ecosystem and elaborate how climate change will affect land use of your choosing in that ecosystem.

Soil's Role in the Carbon Cycle

Carbon Pools

Among terrestrial ecosystems, plants and soils represent by far the largest pools of carbon. The total amount of carbon in the world's soils is estimated to be 1500 Pg (one pentagram of carbon is equal to 1 billion metric tons of carbon) and the fluxes in and out of this pool are important to the amount that ends up in the atmosphere.

Most carbon in soil is stored as **soil organic carbon**, derived from dead plant materials and microorganisms. Soil organic matter comes in many forms. It can be the bodies of dead plants and animals that have not yet been decomposed, live microorganisms, small and simple carbon compounds that are easily decomposed by microorganisms, or more complex carbon compounds that resist decomposition. As soil depth increases, the abundance of organic carbon decreases. Much of the fresh plant bodies and small, simple carbon compounds belong to a pool known as **labile** organic matter, which is very easily decomposed by microbes and will not stay in the soil very long. Some labile organic matter will be transformed by microbes into other forms of organic matter, which do not decompose very easily. This is known as **recalcitrant** organic matter (and can include some of the harder to decompose plant material). The balance between these two pools, and the rate at which labile organic matter is transformed into recalcitrant organic matter, can determine how quickly organic matter is decomposed and the carbon released as CO_2 emissions. Some of this labile and recalcitrant organic matter, if it gets buried or is otherwise prevented from decomposing, may be converted into fossil fuels—but this is over a very long period of time. Until humans started to extract fossil fuels and burn them (releasing long stored pools of carbon), they were removed from the daily and yearly fluxes of the rest of the carbon cycle.

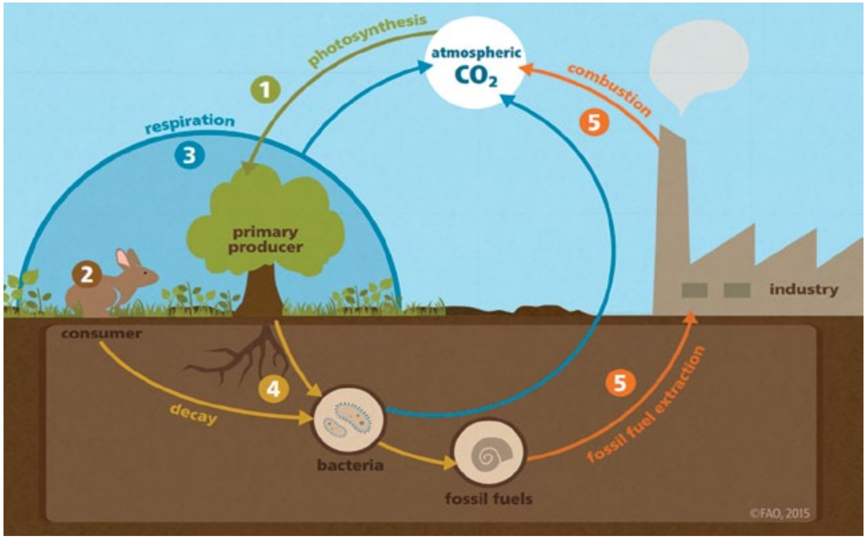
Carbon Fluxes

The movement of any material from one place to another is called a flux and we typically think of a **carbon flux** as a transfer of carbon from one pool to another. Fluxes are usually expressed as a rate with units of an amount of some substance within a certain area being transferred over a certain period of time (e.g. g cm^{-2} s^{-1} or kg km^{-2} yr^{-1}). A single carbon pool can often have several fluxes that cause carbon to be added and lost carbon simultaneously. For example, the atmosphere has inflows from decomposition (CO_2 released by the breakdown of organic matter), forest fires and fossil fuel combustion and outflows from plant growth and uptake by the oceans.

Additions

Carbon addition to the soil (called **sequestration)** occurs when carbon from the atmosphere is captured through physical, chemical or biological processes. This is mostly through **photosynthesis** (Fig. 6; #1), when plants take up CO_2 from the air and store the carbon in their biomass. Some biomass will pass through the food chain as animals consume it (Fig. 6; #2). When they die, some of the biomass from their bodies will end up in the soil, where it may join the **soil organic matter** pool (Fig. 6; #4).

FIGURE 6. *Simplified global carbon cycle.* **(Source: FAO 2015)**



Losses

Carbon losses (also known as **greenhouse gas emissions**) occur when carbon is lost from the soil. Organic matter is **decomposed** by microorganisms back into CO_2 or CH_4 (methane) through a process known as **respiration** (#3 in Figure 6). Plants and animals also respire CO_2 (as you do when you breathe) but to a lesser extent than microbes. In microbial respiration, mostly **labile** organic matter is decomposed. Microorganisms are, generally speaking, happiest in situations of moderate temperature and water, with enough oxygen access (like us, most microorganisms need oxygen in order to survive). In these cases, microorganisms transform carbon into CO_2 and emit it back into the atmosphere.

In situations where there is too much water, and therefore not enough oxygen, for the microorganisms to convert carbon into CO_2, some organisms will start to convert carbon into CH_4. This is a slower process than respiration to CO_2; however, is a stronger greenhouse gas than CO_2 and can have a proportionally larger impact on climate change.

Another loss of carbon from the soil is the loss to lakes and oceans. This can occur through **runoff** – during rain events, soil is washed away into rivers and streams, where it can eventually make it to lakes and rivers. Any carbon trapped in the moving soil may be more easily exposed to decomposition. Loss can also occur though **leaching**, where small pieces of organic carbon dissolve in water and carry through the soil to water bodies. This increases the ocean's organic carbon store as well as exposes the carbon to decomposition from aquatic organisms.

Carbon Balance

The balance (**C balance**) between the fluxes carbon sequestration and carbon loss determines whether soil is accumulating carbon (is a carbon **sink**) or if it is emitting carbon (is a carbon **source**). Some ecosystems can be sources at one time and sinks at another.

$$C\ balance = C_{inputs\ (photosynthesis)} - C_{outputs(respiration)}$$

For example, in the boreal forests of Canada, trees and other plants photosynthesize the most during the summertime, when there is more warmth and sunlight. While the trees and the soil are respiring at the same time, they are photosynthesizing enough to have a net gain of carbon into the system, which will go partly into the trees themselves, into other animals into the system, and into the soil. In the summer, the forests are a carbon **sink**. In the wintertime, however, there is less sunlight and the plants slow and/or stop photosynthesizing. However, they are still alive, and they do not stop respiring. Even though it is colder, microorganisms continue to break down organic compounds and release CO_2. Therefore, in the wintertime, the forests are a carbon **source**. Whether they are, in total, a net sink or source depends on how much they photosynthesize over the summer and how much is lost in the winter.

Carbon Balances in the Northern Hemisphere

Northern ecosystems are a good example of this delicate balance. Historically, soil in northern boreal or taiga ecosystems is a **carbon sink.** The cold and short growing season mean that plants in these ecosystems grow relatively slowly, and therefore accumulate carbon in their biomass only very slowly. However, this same cold climate means that decomposition is even slower – in areas where the ground is permanently frozen and the soils are often saturated, even relatively **labile** organic matter can build up in these soils (creating **Organic** soils, or bogs). Up to 30% of the world's terrestrial carbon may be stored in the soils and plants in these northern ecosystems.

However, as the climate warms, these ecosystems warm too. Permafrost, which has stored labile carbon in frozen layers for millennia, is thawing across the boreal and tundra zones (Figure 7). If accompanied by drier conditions, decomposition may increase dramatically (especially CO_2 emissions) and lead to these systems becoming a carbon **source** where they used to be a **sink**.

FIGURE 7. ***Permafrost collapsing*** *in an Alaskan peat bog, causing trees to fall over as they lose their structural support* **(Photo: Wikimedia)**

Questions Worth Investigating

1. In warm and moist ecosystems, where soil has a very high decomposition rate, what would need to happen in order for the ecosystem to be a carbon sink?
2. a) Can you name one thing that humans could do to change a soil from a carbon sink to a carbon source?
   b) What about changing a soil from a carbon source to a carbon sink?

SECTION 6 Land Conversion and Its Effect on Soil Carbon

Soil Organic Matter and Land Conversion

Through photosynthesis, plants create biomass using CO_2 from the air. Once the plant dies, its biomass decomposes in the soil. During decomposition, the plant biomass is either returned back into the air as CO_2 or remains in the soil as soil organic matter (SOM). Eventually even the SOM will be decomposed and released, but the process is much slower than the decomposition of newly added plant biomass. The amount of SOM in a soil is determined by the balance between SOM being decomposed and new biomass being converted into SOM. By changing the land from its original state humans can affect amount of SOM found in the soil.

Land conversion describes changing the land from one state to another. Usually, land conversion happens when humans want to use natural areas for agriculture, resource extraction, habitation and industrial activity (Figure 8). Land conversion plays a role in the global carbon cycles since this activity can affect the balance between SOM additions and losses.

FIGURE 8. *Conversion of Amazonian rainforest to soybean production* **(Photo: C. Azevedo-Ramos, FAO)**

Land Conversion of Forests

Land conversion of forests is occurring rapidly all around the world. Converting forests to other land uses such as agriculture, usually involves complete removal of forest vegetation, which disrupts the SOM balance in the soil. Converted forest soils are often burned, which removes any remaining plant biomass from the original forest and quickly releases greenhouse gases to the air as products from combustion. Additionally, when the trees are gone the soil is exposed directly to the sun. The now exposed soil will have a higher soil temperature, which can cause much of the remaining SOM to become carbon dioxide. However, under certain circumstances, when forested areas are converted to grasslands some SOM will be added back into the soil by the new grassland plants.

The carbon emissions resulting from land conversion in forests can be large. In Latin America, land conversion of forests is responsible for 46% of the carbon dioxide emissions in the region. In Brazil, about 2.5 million hectares of forest are converted every year and this is responsible for around 52% of Brazil's annual greenhouse gas emissions. In Southeast Asia, every year large tracts of native forest are converted to plantations for many products such as palm oil. Many of these forests are unique tropical peatlands, which in their natural state store large amounts soil C, but will release soil carbon after being converted (Figure 9). Converting one hectare of tropical peat forest to palm oil plantation will emit, on average, the same amount of carbon dioxide as 12 passenger cars per year during the first 25 years of the plantation. Currently millions of hectares of peat forests have been converted to palm oil production and thousands more being converted every year. Overall, the total emissions from palm oil production is substantial at approximately 1.4 Gt/year and rising (United Nations Environment Programme, 2007). The amount of carbon emitted by converted peatlands represents roughly 5% of global human carbon emissions based on 1990 emission levels.

FIGURE 9. *Deforestation of Sumatran peat forests for palm oil production* **(Photo: "Riau deforestation 2006" by Aidenvironment, 2006)**

Land Conversion of Grasslands

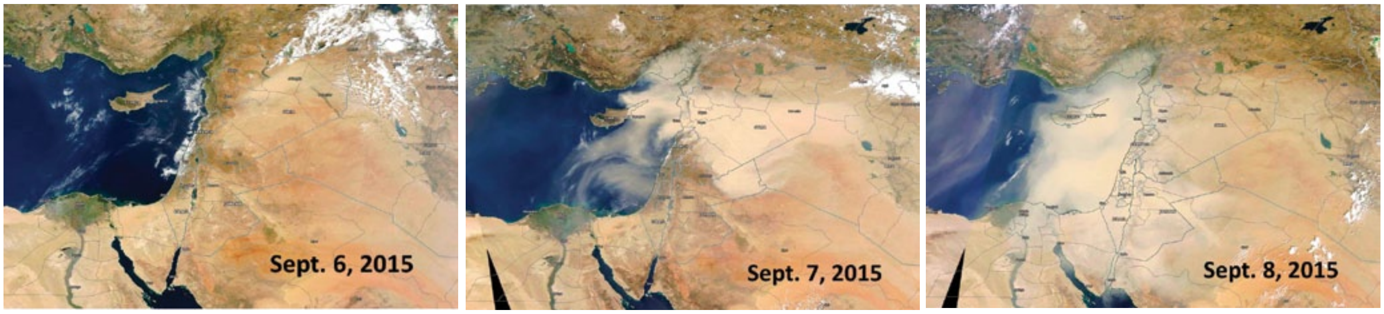
Grasslands cover approximately 40.5% of Earth's terrestrial surface outside of Greenland and Antarctica. By their nature, grassland soils store carbon by generating large amounts of plant-root biomass every year. Under natural conditions, grassland vegetation protects soil carbon from wind erosion and buffers the soil from the effects of direct sunlight. However, the climate where grasslands soils thrive is also suitable for crop growth and animal pasture. Around the world, most grasslands are either used as pasturelands or have been converted to fields for agricultural crops. Native grassland vegetation has large root systems, which eventually die and add organic matter to the soil. Agriculture often involves tilling the soil, which breaks up the natural soil structure and adds oxygen to it. The higher amount of oxygen in the soil stimulates the soil microorganisms to break down SOM at a faster rate. When considering these two factors together, converting grasslands to croplands can result in a rapid loss of SOM back to the atmosphere. The SOM also happens to be the glue required for good soil aggregation. Since the original plant biomass is now gone, these biotic glues are not replaced and soon soil structure becomes weak leading to other land management problems and larger potential for soil erosion and further carbon loss.

FIGURE 10: *A dust storm in Spearman, Texas* **(Photo: Wikimedia)**

In the US and (to a lesser extent) Canadian prairies, the early 20th century saw a massive increase in the conversion of grasslands into agricultural croplands, which was enabled by unusually high rainfall during that time. When weather returned back to its typical arid to semi-arid conditions, inappropriate management techniques that left the soil surface without any vegetative cover increased the chances of wind erosion. These land use decisions became a problem when a severe drought occurred in the 1930s and crop production in these areas became impossible. Large dust storms (Figure 10) dominated the region as the poor management practices had destroyed the soil structure and along with it, the SOM. Ultimately, as a result of the Dust Bowl in the US, 2.5 million people had to leave their homes and resettle in other areas. This enormous disaster lead to establishment of various soil conservation practices and initiation of programs to conserve soil and restore ecological balance.

Even now, soil erosion continues to some extent in North America but dust storms today are much less severe and occur less frequently. Unfortunately, intensive agriculture and land management practices in other areas of the world such as China have created new dust bowl conditions which severely impact the population of the region and the effects can be even seen from space (Figure 11).

FIGURE 11. *Satellite view of a dust storm traveling across the Middle East in September, 2015.* **(Photo: Wikimedia)**



Recovering Soil Organic Matter

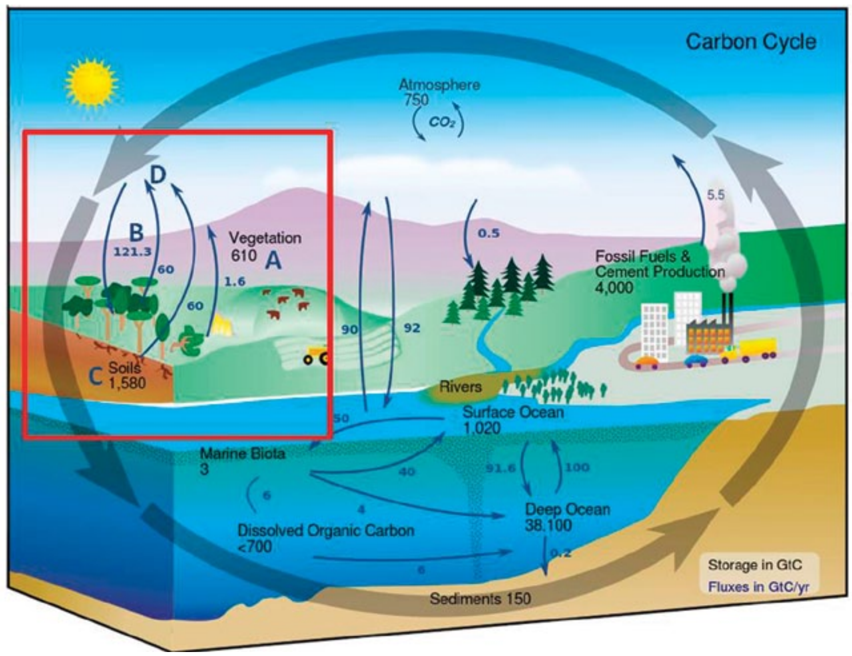
Managing soil carbon through land use is one of the strategies for tackling global climate change. Reforestation projects in the Amazon rainforest have shown that the carbon lost during land conversion of these areas can be recovered from the atmosphere by re-establishing new biomass inputs into the soil. Many farmers in North America and around the world and are using the lessons learned from the mistakes of the early 20th century and now limit soil tillage (Figure 12), leave crop residues on the soil after harvest, and use cover crops in-between growing seasons. These land management practices protect the soil as they prevent wind erosion and provide plant biomass that is converted to SOM.

Famers who use these land management techniques have also realized that promoting SOM formation in the soil is good for crop growth and benefits long-term soil productivity. As an added benefit, the SOM that these cropping systems add to the soil help remove carbon from the atmosphere. By managing croplands and other converted lands for SOM, humans now have a means to recover the carbon lost from soils through land conversion and poor management practices. These management strategies can be employed throughout parts of the world where SOM is currently under threat. In the future, managing converted lands to increase SOM could be an effective strategy to help offset carbon emissions from other human sources.

FIGURE 12. *Zero-till corn with straw residue covering soil surface* **(Corn and Soybean Digest, 2015)**

Questions Worth Investigating

Adapted from the Simple carbon Cycle (Wikipedia) Black numbers indicate the amount of carbon stored within that part of the carbon cycle in billions of tons and purple arrows indicate the amount of carbon entering or leaving that part of the carbon cycle.



Use the diagram of the carbon cycle above to answer the questions (Answer Key Follows):

1. In the red box, **A** represents the total amount of carbon found in vegetation and **B** represents the amount of carbon being removed from the atmosphere every year by plants. How would **A** and **B** change when land conversion reduces vegetation? Would the numbers increase or decrease? Why?
2. In the red box, carbon represents the total amount of carbon found in soil and **D** represents the amount of carbon lost from the soil each year. How would these numbers change if land conversion reduces new plant biomass from entering the soil and exposes the soil to sunlight? Would the numbers increase or decrease? Why?
3. In the yellow box you can see the other sources of carbon and the total amount of carbon in the atmosphere. If we assume human carbon emissions do not change, how would the effects described in 1 and 2 influence the overall number for atmospheric carbon? Would the number increase or decrease? Why?
4. What areas of the carbon cycle would be affected if land practices that focus on soil organic matter management were used around the world? How would these practices affect the areas of the carbon cycle you looked into in questions 1, 2 and 3?

Glossary

B

Brackish water—salt and fresh water mixed together

C

Carbon balance—the balance between carbon additions and losses to a system—determines whether a pool is a carbon sink or source

Climate—the long-term pattern of weather of a particular location including temperature, humidity, wind, precipitation and other meteorological information

Climate change—long-term variations in climate; can be naturally occurring, or caused/ accelerated by human activity

D

Decomposition—the process by which organisms (e.g., microorganisms, fungi) break down organic matter into simple, non-organic molecules such as carbon dioxide

F

Fluxes (carbon)—processes that transfer carbon from one pool to another

G

Global carbon cycle—all of the major carbon pools and fluxes on Earth

Greenhouse effect—phenomenon in which the Earth's atmosphere traps some of the sun's energy and keeps the surface temperatures on Earth warm

Greenhouse gases—gases that contribute to the greenhouse effect by absorbing energy from the sun or the Earth and re-emitting it as heat (primary greenhouse gases are carbon dioxide, methane, nitrous oxide, and water vapour)

Greenhouse gas sink—when a pool of carbon or nitrogen stores more greenhouse gases than it releases

Greenhouse gas source—when a pool of carbon or nitrogen produces more greenhouse gases than it stores

H

Hydrology—the branch of science concerned with the properties of the Earth's water, especially its movement in relation to land

L

Labile organic matter—organic matter, which is easily decomposed by microbes

Land conversion—the change of land from one land use to another

Leaching—the loss of water-soluble (dissolved) nutrients from the soil, typically in water

O

Organic soil order—a soil order (in Canadian soil classification system) associated with the accumulation of organic materials (peat) in water-saturated conditions

P

Permafrost—soil, rock or sediment that has been frozen for 2 or more consecutive years.

Photosynthesis—the process in a plant, which converts carbon dioxide into plant biomass, and stores energy for the plant (and all other living things)

Podzolic soil order—a soil order (in Canadian soil classification system) associated with coniferous vegetation and igneous-rock type of parent material. High rainfall (in association with high acidity) leaches ions from top horizons of the soil profile to lower parts of the profile where iron and aluminum accumulate creating orange-coloured B horizon

Pools (carbon)—places in which carbon is stored

R

Recalcitrant organic matter—organic matter which is resistant to decomposition by microbes, and will break down more slowly than labile organic matter

Respiration—the process through which organisms release energy; a byproduct of this process is usually carbon dioxide

Runoff—water from precipitation travelling over the surface of the soil; can often wash soil away with it

S

Sequestration—the process by which carbon is added to a pool (e.g. the soil, or oceans), usually from the atmosphere

Soil hydrology—the study of the properties, distribution and effects of water on soil

Soil organic carbon—carbon stored in organic molecules in the soil, from dead plant materials and microorganisms

Soil organic matter—plant and animal residues occurring in the soil at various stages of decomposition as well as cells and tissues of soil organisms and substances synthesized by soil organisms

W

Weathering—the breakdown and changes in rocks, soil and sediments at or near the Earth's surface produced by biological, chemical, and physical agents or combinations of them

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