

# Soils and Decomposition

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Soils are dynamic, complex systems of inorganic, organic and biotic components that have the capacity to support plant life. Soils are classified on the basis of their chemical and physical properties. Decomposition of organic matter is the principal process in soils that recycles plant nutrients and produces humus.

## Overview of Soil Types

Soils are classified on the basis of their dominant chemical and physical properties. Properties that are considered include extent and nature of soil formation, climate, topography, base saturation, clay mineralogy, and amount of organic matter.

## Soil profiles and diagnostic horizons

Soil properties change with depth. Layers of soil that are nearly parallel with the soil surface and that are distinguishable from adjacent layers are called soil horizons. Horizons are visible on the vertical wall of a pit dug into the soil; the entire series of horizons visible on this wall is known as a soil profile. An idealized soil profile is illustrated in **Figure 1**.

Soil classification requires an examination of the soil profile. Some of the major soil classes are identified on the basis of particular soil horizons known as diagnostic horizons. Diagnostic horizons that occur near the surface include mollic and umbric. Mollic horizons are dark in colour, have more than 1% organic matter and greater than 50% base cation saturation. Umbric horizons are similar to mollic, but have less than 50% base cation saturation. Diagnostic subsurface (B) horizons include argillic horizons that are created by the accumulation of clay that has moved into the horizon. Other subsurface diagnostic horizons are the cambic, which is weakly coloured, and the spodic, which forms due to an accumulation of humus or iron and aluminium hydrous oxides.

## Soil taxonomy

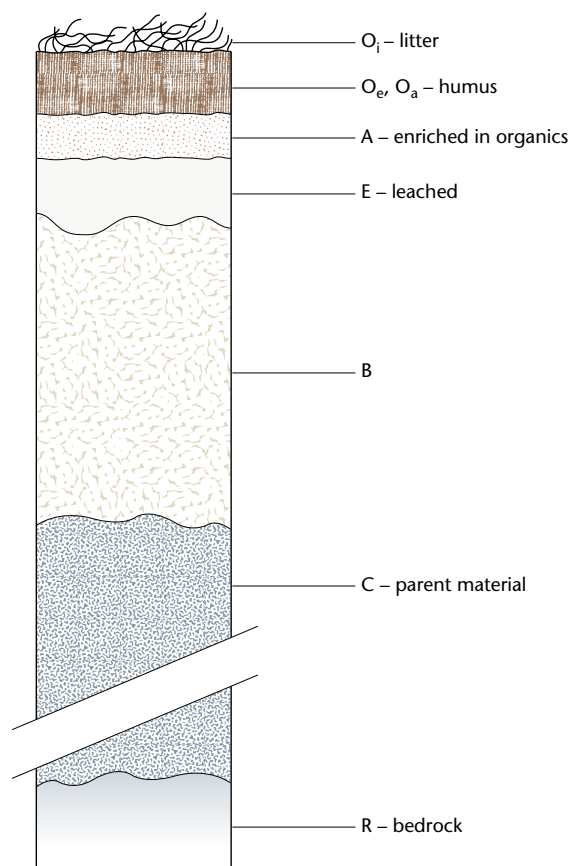
The most widely used soil classification scheme is that of the Food and Agriculture Organization of the United Nations (FAO). The FAO system contains 26 soil classes, which are listed in **Table 1**. Individual nations may have their own scheme for soil taxonomy. For example, both Canada and the United States have their own systems of soil classification.

At a finer level of resolution, soils are classified into very specific groups. Indigenous peoples often have a classification scheme unique to their geography and agricultural

## Introductory article

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**Figure 1** Idealized soil profile. Many soils lack one or more of the master horizons or layers (O, A, E, B, C, R). O-horizons are dominated by organic material. A-horizons are formed at the surface or beneath an O-horizon and are characterized by either humified organic material or surface disturbances such as pasturing or cultivation. E-horizons are characterized by a loss of clay or minerals, leaving a higher concentration of sand and silt. B-horizons are commonly called subsoil and are characterized by an influx and accumulation of clays. C-horizons show little soil development and often resemble the parent material. R-layers are bedrock. Subscripts are used to indicate particular characteristics. For example O<sub>i</sub>, O<sub>e</sub> and O<sub>a</sub> denote organic horizons in which the litter is slightly decomposed (i), intermediately decomposed (e), or highly decomposed (a).

**Table 1** Soil classification. FAO soil classes, approximate relationship to US soil orders and common characteristics of each FAO class

FAO classification (soil class)	US classification (soil order)	General characteristics
Acrisols	Ultisols	Highly weathered, low base saturation (<50%), argillic horizon
Andosols	Andisols	Derived from volcanic ejecta, usually low bulk density
Arenosols	Entisols	Sandy soils, poorly developed, no diagnostic horizons
Cambisols	Inceptisols	Weakly developed soils with a cambic or umbric horizon
Chernozems	Mollisols	Deep, nearly black mollic horizon
Ferralsols	Oxisols	Highly weathered tropical soils
Fluvisols	Entisols	Young soils developed on alluvial deposits
Gleysols	Many orders	Very wet soils, but not organic
Greyzems	Mollisols	Deep, dark grey mollic horizon
Histosols	Histosols	Organic soils
Kastanozems	Mollisols	Deep, dark brown surface horizon, high calcium content
Lithosols	Many orders	Shallow (<10cm) over hard rock
Luvisols	Alfisols	Argillic horizon
Nitisols	Alfisols/Ultisols	Argillic horizon with even distribution of translocated clay
Phaeozems	Mollisols	Deep, dark grey mollic horizon
Planosols	Many orders	Flat, poorly drained soils
Podzols	Spodosols	Translocation of humus downward
Podzoluvisols	Alfisols/Mollisols	Transition between podzols and luvisols
Rankers	Inceptisols	Steep, shallow soils
Regosols	Entisols	Thin, weakly developed soils
Rendzinas	Mollisols	Deep, dark surface horizon with high lime
Solonchaks	Aridisols	Saline desert soils
Solonetz	Aridisols	Sodic desert soils
Vertisols	Vertisols	Contains >30% swelling clays
Xerosols	Aridisols	High calcium desert soils
Yermosols	Aridisols	Desert soils

practices. In the United States, the soil series is the most exclusive level of classification and over 20 000 unique soil series have been identified.

content), the physical characteristics of a soil set limits on how that soil may be used.

## Physical Characteristics of Soils

Soil physical properties include texture, density, porosity, structure, water content, strength and colour. Because physical properties of soil change very slowly over time and are not readily changed by management (except for water

## Texture

Soil texture is perhaps the most important single physical characteristic with regard to soil fertility and soil engineering properties. The mineral components of soil can occur in a wide range of particle sizes. Particles larger than 2.0 mm in diameter are considered fragments and are not included in a textural analysis. Among particles smaller than 2.0 mm in diameter there are three distinct particle size classes.

Sand is the coarsest and ranges from 0.05 to 2.0 mm in diameter. Silt is the intermediate size class and ranges from 0.002 to 0.05 mm in diameter. Clay includes all particles smaller than 0.002 mm in diameter.

The proportion of particles in each size class determines the textural class of a soil. Although numerous different schemes exist for classifying soil texture, that adopted by the US Department of Agriculture is typical. Using a textural triangle (Figure 2) soils can be assigned to one of 12 textural classes.

## Bulk density, porosity, and structure

Most other physical properties of soils are related to textural class. Bulk density, which is defined as the oven-dry soil mass divided by the volume of that soil, is usually lowest in clay soils and highest in sandy soils. This appears to be in contrast to common terminology that refers to clay soils as heavy and sandy soils as light. This terminology reflects the cohesion of the contrasting soils and the amount of work required for tillage. Clay soils have bulk densities in the range 1.1–1.3 Mg m<sup>-3</sup>. Bulk densities of sandy soils are in the range 1.7–1.9 Mg m<sup>-3</sup>. Bulk densities

can be increased by compaction and decreased by cultivation and incorporation of organic matter.

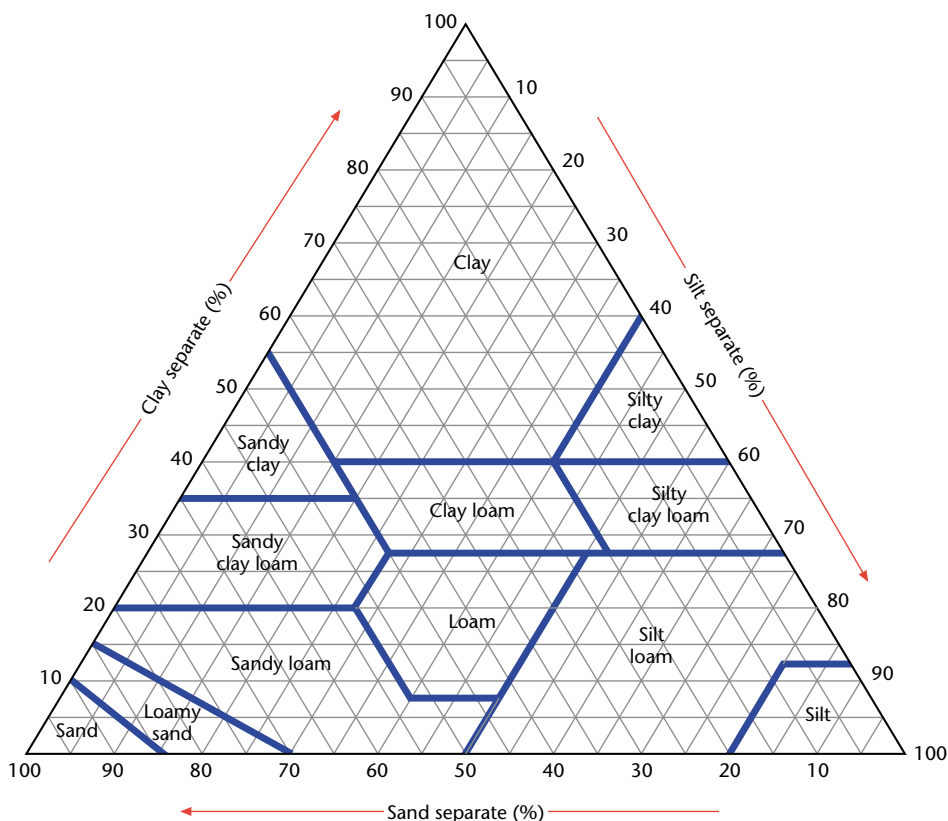
Bulk density, in turn, influences soil porosity. Porosity is the percentage of soil volume that is filled with air and water. Porosity increases as clay content increases. However, permeability, the ability of water or air to move through a soil, generally decreases with increased clay content.

In most soils, the primary soil particles are cemented together into larger units known as peds. The structure of a soil is based on the shape, size and coherence of these peds. Structure can be important because it influences the movement of air and water into a soil.

## Water availability and potential

Water availability in a soil determines the type of vegetation that can exist on that soil. Water availability is determined by both climate and soil properties. The movement of water in a soil is determined by water potential.

Water potential is a measure of the work that water can do if it moves from its current state to a reference state. The



**Figure 2** Textural triangle. Soils textural classes can be determined on the basis of the percentage of sand, silt and clay. Knowing any two of these percentages allows the determination of textural class. From US Department of Agriculture (1996), *Keys to Soil Taxonomy*, 7th edition.

reference state is taken to be a pool of water at a relative elevation of zero. Thus a flooded soil with water standing on the surface has a water potential of zero. Non-flooded soils will all have negative water potentials, indicating that work must be done on the water to bring it to the zero reference state. Water potential is measured in kilopascals (kPa,  $1 \text{ Pa} = \text{kg m}^{-1} \text{ s}^{-2}$ ).

As flooded soils dry, water may be removed by gravitational flow through the soil, runoff over the soil surface, evaporation from the soil surface and transpiration through the plant vascular system. After all water is lost that can be removed by the pull of gravity, the soil is said to be at field capacity and the water potential is about  $-33 \text{ kPa}$ . Continued removal of water is due to evaporation and transpiration. When the soil no longer has enough water to keep plants alive it is said to be at the permanent wilting point, which occurs at a water potential of about  $-1500 \text{ kPa}$ . The amount of water present between field capacity and permanent wilting point is the plant-available water. Sandy and clayey soils have relatively low plant-available water; soils with a mix of particle sizes, known as loams, have the greatest amount of plant-available water.

## Temperature and colour

Soil temperature influences both physical and biological process in soils. Although soil temperatures closely reflect average air temperatures in the area, other factors influence temperature including vegetative cover, topography, soil colour and water content. Plants will germinate and grow faster in warmer soils. Excessively high temperatures may cause excessive drying or damage to germinating or growing plants. Evaporation will be greater from warmer soils.

Soil colour is often used as an indicator of soil properties or processes. For example, soils with poor aeration often have grey, blue or green colours. Soil colour is classified according to the Munsell colour notation. This system classifies colours according to three properties: hue, value and chroma. Hue is the dominant spectral colour (red, yellow, blue and green). Value is the relative darkness on a scale of 0 to 10 with 0 being black. Chroma is a measure of the purity of colour, also on a scale of 0 to 10 with 10 being the most brilliant or pure.

## Chemical Characteristics of Soils

The chemistry of soils is the chemistry of colloids and cations. Colloids are substances whose particles are so small that their surface properties are more important than their mass. Cations are positively charged ions that include most, though not all, of the essential nutrients for plants.

## Colloids, clays, humus and cation exchange

Colloids are too large to pass through a semipermeable membrane and too small to settle out of an aqueous solution. Their size ranges from  $1 \mu\text{m}$  to  $1 \text{ nm}$  in diameter. As a result, colloidal particles provide most of the surface area within a soil. The nature of this surface area influences nutrient and water dynamics within the soil and physical characteristics of the soil.

There are two principal types of colloidal particles in the soil: organic and mineral. Organic colloids are known as humus and are the products of decomposition of organic residues. Mineral colloids are known as clays and originate in several different ways. In general, clays are not simply finely divided particles of parent material, but are formed by crystallization or dissolution.

Most soil clays are crystalline and the crystal structure is organized around ions of silica and aluminium. Amorphous clays lack crystalline structure. A variety of clays are created as iron and magnesium and other ions are substituted for aluminium. A very important property of clays is their potential for expansion when wet. For example, smectites, such as montmorillonite, swell extensively when wet. In contrast, kandites, including kaolinite, do not shrink and swell.

Both clay and humus colloids have a net negative charge on their surface. This gives rise to an extremely important property of soils, cation exchange. Colloidal particles can attract and hold cations on their surface. Cations in the soil solution can replace cations on the colloidal surface. The proportions of various cations in the soil solution and on the surface of the colloids change as plants take up nutrients, as weathering and decomposition release nutrients to the soil, and as protons are added to the soil.

## Cations, cation exchange capacity, and base saturation

Cations are held in the soil on cation exchange sites. The most abundant cations found on exchange sites in a typical soil are calcium ( $\text{Ca}^{2+}$ ), magnesium ( $\text{Mg}^{2+}$ ), potassium ( $\text{K}^+$ ), sodium ( $\text{Na}^+$ ), hydrogen ( $\text{H}^+$ ), and aluminium hydroxide ( $\text{Al}(\text{OH})$ ). Ammonium ( $\text{NH}_4^+$ ) is not as abundant, but is the major nitrogenous cation. The strength with which these cations are held by exchange sites varies and increases in the following order:

Thus, sodium can be readily displaced from cation exchange sites and is most readily leached from soils.

Cation exchange capacity (CEC) is the total amount of exchangeable cations that a soil can hold. The amounts and types of soil colloids present determine the CEC. CEC is measured in units of centimoles<sub>c</sub> per kilogram of soil. Typical values range from less than  $5 \text{ cmol}_c \text{ kg}^{-1}$  in sandy soils to more than  $100 \text{ cmol}_c \text{ kg}^{-1}$  in organic soils.

The cations that are absorbed on exchange sites can be divided into two groups: base-forming and acid-forming.

Acid-forming cations are hydrogen and aluminium. Base-forming cations include calcium, magnesium, sodium, potassium and most others. Base cation saturation percentage (BCSP) is simply the percentage of CEC that is filled with base-forming cations. As soil acidity increases, BCSP decreases.

## Soil reaction or pH

Natural processes tend to acidify soils. Base-forming cations are leached from soils, carbonic acid is formed from carbon dioxide, plant roots excrete organic acids, and decomposition produces acidic products. In addition, acid precipitation adds  $H^+$  and crop removal depletes basic cations. Soil basicity is less common, but may occur in arid regions or due to soil parent material or soil amendments.

Soil reaction is measured in pH units, with pH defined as the negative logarithm of the active hydrogen ion ( $H^+$ ) concentration in moles per litre. Soil pH values fall between 4 and 10, and most plants grow best at values between 5.5 and 8.5. Extreme values of pH have negative effects on nutrient availability. Strongly acidic soils often have toxic levels of soluble aluminium and manganese. Many essential nutrients form insoluble precipitates in soils with high pH.

Measuring pH determines the concentration of hydrogen ions in solution, known as active acidity. However, 10 to 1000 times more hydrogen ions are bound to exchange sites. Adding basic cations, usually in the form of lime ( $CaCO_3$ ), to soils will neutralize some of the soluble hydrogen ions and displace some of the bound hydrogen ions. Thus the change in pH resulting from the addition of lime is less than would be expected on the basis of active acidity alone.

## Overview of Decomposition Processes

Decomposition is the breakdown, by physical and biological mechanisms, of organic substances found in the soil. Plant remains, deposited on or in the soil, are known as plant litter. Concomitant with the breakdown of litter is the synthesis of meta-stable substances known as humus. During decomposition inorganic substances including plant nutrients are both released (mineralized) from and incorporated (immobilized) into the decaying material. Animal remains are qualitatively quite different from plant remains. Although animal remains may be locally significant, they represent a very small proportion of the organic matter input to a soil and will not be further discussed.

## Mechanisms of organic matter decomposition

Physical processes often dominate the early stages of decay in natural organic materials. Leaching of soluble

substances from the organic residues may account for as much as 25% of the mass lost from some litters. Much of the soluble substance is simply moved from the decaying substrate into the soils where biological processing occurs. Freeze–thaw or wet–dry cycles may contribute to fragmentation of residues.

Most of the decay process is biologically mediated. In soils, bacteria and fungi are the major microbial agents of decay. Microbial biomass varies greatly both spatially and temporally and often occurs with a patchy dispersion pattern. Microbial biomass ranges from less than 100 to more than 3000  $\mu g$  of carbon per gram of soil. Expressed on an areal basis, bacterial and fungal biomass generally falls in the range of 10 to 300  $g\ m^{-2}$  in the top 15 cm of soil.

Fungi and bacteria function similarly with regard to decomposition. Soluble substances such as sugars and low-molecular weight phenolic compounds are assimilated by the microorganisms and metabolized. However, a large fraction of plant litter is composed of high-molecular weight polymers such as celluloses, lignin and suberin, which cannot be directly assimilated by microorganisms. Rather, extracellular enzymes must first break them down. In the case of cellulose, the polymer is hydrolysed into mono- and oligosaccharides that are readily assimilated. In the case of lignin and other phenolic substances, the enzymes can catalyse both a degradation of high-molecular weight polymers and a condensation of low-molecular weight phenolics. In the latter case, new organic molecules are synthesized that differ from those found in the plant litter.

Decomposition is a critical process in the nutrient dynamics of a soil. As litter decomposes, microorganisms become inextricably associated with the decaying litter creating a substrate–microbe complex. The microorganisms will decay the litter in order to gain carbon, nutrients and energy for growth and reproduction. In most freshly deposited plant litter, carbon and energy are relatively abundant and inorganic nutrients are in short supply. In order for the microbial community to produce enzymes, adenosine triphosphate (ATP) and other essentials of metabolism it must accumulate nitrogen, phosphorus and sulfur and perhaps other nutrients from the environment. Thus, during early stages of decomposition, nutrients are imported into the substrate–microbe complex, a process called immobilization. As carbon is released via respiration, the ratio between carbon and other nutrients declines. Eventually the concentration of nutrients is sufficient to meet the needs of the decomposer organisms and both carbon and nutrients will be released from the complex. The process of nutrient release is called mineralization. In any given substrate–microbe complex the processes of immobilization and mineralization occur simultaneously, with the difference between the two processes, net mineralization, determining whether or not nutrient will be released into the soil.

Microorganisms often live in association with other soil fauna. This soil fauna may facilitate microbial decomposition by acting as symbiotic hosts and by ameliorating the environment or the organic substrates for microbial attack. For example, termites and earthworms have microbial communities within their guts that are capable of degrading organic polymers into soluble organic compounds. Some fauna fragment larger particles into smaller ones, increasing the surface area available for microbial attack. Other fauna incorporate organic matter into faecal pellets that may provide environments in which decay is enhanced. In addition, fauna aid in aeration and mixing of the soil, which also influences decay rates.

## Models of decomposition

Early stages of decomposition are frequently modelled using a negative exponential decay model with a constant decay rate.

$$M_t = M_0 e^{-kt}$$

where  $M$  is mass,  $k$  is the decay constant and  $t$  is time (duration) of decay.

This model provides a good fit to mass loss over time for many types of litter during their initial stages of decay. However, litter is not a homogeneous material and some portions are more readily decomposed than are others. In addition, meta-stable humic compounds are produced during decay and nutrient availabilities change. Thus a better model of decay would reflect the changing decomposability of the litter as it decays. Although numerous improved models for long-term organic matter decay are in existence, there is not currently a generally accepted model.

## Chemical Characteristics of Soil Organic Matter and Litter

Plant litters are highly variable in their composition, but they all share certain common components. Carbohydrates and lignin are the two most abundant classes of chemical compounds. Soluble phenolics such as tannins and insoluble substances such as cutin and suberin may be low in concentration but may influence the decomposability of the substrate. Most soil organic matter is classified as humus. Humus includes a wide variety of high-molecular weight, colloidal substances, which are relatively resistant to decay.

### Carbohydrates: celluloses and hemicelluloses

Carbohydrates make up the bulk of most litter. Soluble carbohydrates are predominantly mono- and oligosaccharides and are readily metabolized by soil organisms. Polymeric carbohydrates are hemicelluloses and celluloses.

Cellulose is the principal fibre that gives plants their basic structure. Hemicelluloses add cohesion to the cell wall.

Celluloses are very long unbranched strands of  $\beta$ 1–4-linked glucose units. Although insoluble, their repeating unit structure makes them readily degradable by cellulase enzymes. Hemicelluloses are more complex; they are composed of branched polymers that contain several different sugar monomers. Hemicelluloses are variable in their decomposability.

### Lignin

Lignin is a highly complex and variable macromolecule found in woody plants. Lignin gives rigidity and decay resistance to plants. The fundamental building blocks of lignin are a group of closely related phenyl-propane units including coumaryl, sinapyl and coniferyl alcohols. These are bound together with a variety of covalent bonds to create a highly heterogeneous and poorly defined macromolecule. Lignin creates a molecular cage around many of the polysaccharide molecules. The heterogeneous nature of lignin makes it resistant to direct enzymatic attack. Lignin concentration is often negatively correlated with decomposition rates in litter. Because lignin is resistant to decay, its concentration increases during the decomposition process.

### Humus

Humus or humic substances are general terms used to describe amorphous and colloidal soil organic matter. Humic substances include both residues of decaying organic matter and complex substances that were synthesized during the decay process. Humic substances are highly stable and decompose very slowly. They have a very high cation exchange capacity and can have a strong influence on nutrient cycling in a soil. Humic substances are categorized into three distinct groups on the basis of their solubilities: humins, humic acids and fulvic acids.

Humins are not soluble in water at any pH. They have the highest molecular weight, the highest carbon content and the lowest oxygen content of the humic substances. Humins are black.

Humic acids are not soluble in water under acidic conditions, but are soluble in dilute sodium hydroxide. They are the major extractable component among humic substances. They are intermediate to humins and fulvic acids in their chemical properties. They are dark brown to black.

Fulvic acids are soluble in water at all pH values. They have the lowest molecular weight and carbon content of the three humic substances, but contain more oxygen. Most of the oxygen in fulvic acids is associated with functional groups ( $-\text{OH}$ ,  $-\text{COOH}$ ,  $-\text{C}=\text{O}$ ). They tend to be yellow or yellow brown.

The ratio of humic acids (HA) to fulvic acids (FA) changes predictably among soils. Grassland soils (chernozems or mollisols) have an HA:FA ratio  $> 2$ . Forest soils often have an HA:FA ratio of  $< 1$ .

## Climatic Influence on Decomposition

Decomposition is largely a biological process so climatic factors that influence rates of biological process will have similar effects on decomposition. Within the range of conditions normally found at the Earth's surface, decomposition rates generally increase with temperature.  $Q_{10}$  values, the fold-increase in decomposition rate for a 10-degree change in temperature, are usually above 2.0 and below 3.5 for freshly fallen litter if other environmental factors are not limiting.

Moisture availability also regulates rate of decomposition. At suboptimal conditions, mobility of substances in the soil becomes limiting and microbial activity declines. Under saturated or flooded conditions, oxygen diffusion is limited and anaerobic conditions will soon develop. Decomposition rates are slowed and the nature of decomposition products is changed when oxygen is not available. In addition, the water relations of the soil can influence pH and nutrient mobilization, which in turn will influence the activity of decomposer organisms.

Moisture levels also influence leaching. Fresh litter may contain from 1% to more than 20% soluble substances. When water is abundant, these substances are rapidly lost from fresh litter due to leaching and microbial consumption.

The influences of temperature and moisture on decomposition are interactive. Under extreme moisture conditions temperature has much less of an effect on decay rates. Furthermore, climate influences not only the rate of decomposition but also the pattern. For example, the amount of nitrogen released per gram of carbon mineralized varies when identical litters are incubated under different climatic conditions.

## Soil Organisms and Decomposition

Soil organisms can be divided into two groups based on the food web to which they belong. Some soil organisms live in the soil but derive their food from aboveground primary production and are part of the grazing food web. Examples include burrowing mammals, insects and reptiles. Other soil organisms derive their food from detritus and belong to the decomposer food web.

Decomposer organisms are classified on the basis of their size and function. Microflora and microfauna are under  $100\ \mu\text{m}$ . These are the bacteria, fungi, nematodes, protozoans and most rotifers. Mesofauna range from

$100\ \mu\text{m}$  to 2 mm. They include small arthropods, such as mites (Acari) and springtails (Collembola), and small annelids. Macrofauna are larger than 2 mm and are dominated by centipedes (Chilopoda), millipedes (Diplopoda), snails (Mollusca), spiders (Araneae), beetles (Insecta-Coleoptera) and segmented worms (Annelida).

The dominant functional group of decomposer organisms is the absorptive saprotrophs, the bacteria and fungi. They serve the function of depolymerizing the insoluble portions of plant litter. Fungi grow in strands known as hyphae and have the ability to spread over and penetrate larger particles of detritus over relatively long periods of time. Bacteria, in general, have a unicellular growth form and are better adapted to attachment on surfaces and to the exploitation of smaller particles over shorter time periods. These microorganisms also vary in their ability to utilize various organic substances. Some microbes utilize only soluble substrates, but they are highly efficient at exploiting this resource. Bacteria dominate this group. Other microorganisms are able to break down cellulose or lignin. They grow more slowly but play a critical role in the decomposition process. Fungi dominate this group.

Cellulolytic and lignolytic fungi must rely on extracellular enzymes to attack their substrates. In the process, soluble products are released. Many other microorganisms live in close association with these fungi and compete for the extracellular decay products.

Bacteria and fungi are at the base of the decomposer food web. Many of the meso- and macrofauna feed directly on the fungi and bacteria or on one another. Other soil fauna may ingest or fragment litter, but microorganisms living on the litter or symbiotically in the gut generally carry out the chemical breakdown of organic matter.

Earthworms are often the single most abundant group of soil animals. Their numbers and biomass vary tremendously. Numbers range from less than one to over 2000 individuals per metre squared. Because earthworms vary greatly in size, biomass may be a better indicator of their importance, though it is more difficult to determine. Estimates of biomass range from less than 1 to over  $300\ \text{g m}^{-2}$ . Earthworms burrow into the soil and burrows have been found as deep as 6 m. Their numbers frequently range from 5 to  $200\ \text{m}^{-2}$ . These burrows allow water and air to move more quickly into the soil, minimizing runoff and erosion. In addition, earthworms carry large amounts of soil back to the surface. The amounts of soil brought to the surface range up to nearly 5 cm of deposition per year, representing over 250 tonnes per hectare. In some ecosystems borrowing insects such as ants or termites may have similar influences on soil structure and function.

## Further Reading

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