Reading 5
Soil

Soil is different things to different people. To most of us it is something to be washed from clothes and swept out the door. To the geologist soil is the unconsolidated, weathered part of the earth's mantle, an insignificant, small fraction of its total volume. To the civil engineer it is the medium for the support of structures and a construction material. But to the agriculturist, soil is that part of the earth's crust in which the roots of plants grow. It is a vital, living component of the environment–a component that can be manipulated to affect crop performance. When soil is misused, crops become less productive; when handled with due consideration for its biological and physical nature, it can continue to yield crops throughout countless generations of cultivation and use.

Soil has 3 primary functions in sustaining plant life:

1. It supplies mineral elements, serving both as a medium of exchange and as a place of storage.
2. It supplies water and serves as a storage reservoir.
3. It serves as a medium within which the roots of terrestrial plants, as well as those of many aquatic plants, anchor themselves.

One might ask whether soil is really necessary for plant growth. **Hydroponics**—the soilless cultivation of plants with nutrient solutions alone or with sand or gravel—is practiced today on a limited scale. The United States Armed Services use hydroponic gardens to provide fresh vegetables for personnel on isolated islands in the Pacific Ocean where soil is not available. Even though it is possible to maintain a limited agriculture without soil, the massive production of plant materials that the world requires cannot be accomplished economically without soil under present economic conditions.

SOIL SYSTEMS

For the purposes of crop production, soil must be considered to be a delicate balance of interwoven and interacting systems:

1. Inorganic minerals
2. Organic matter
3. Soil organisms
4. Soil atmosphere
5. Soil water.

Although it is convenient to consider each of these systems individually, they are neither separate nor independent in nature. To change one of them results in a change in all. The nature of a soil is greatly modified when one system dominates. For example, a high water table produces a kind of soil that has particular and definite characteristics, no matter where it is found in the world.

Soil Minerals

The inorganic constituents of the soil–soil minerals–are ultimately derived from the parent materials, which are the underlying chemically weathered minerals or organic matter that is the basis of soil. Soil minerals may be **original**, relatively unchanged from the parent minerals (such as quartz in the form of sand), or **secondary**, formed by the weathering of less resistant minerals (such as clays). The amount of inorganic material varies greatly, from more than 99% of the weight of sandy and clayey soils, to as little as 1% in some organic soils. The inorganic component of soils consists of a mixture of particles that differ in size, in composition, and in physical and chemical properties.

Soil Texture

The mineral particles of the soil can be arranged according to size from very coarse to very fine. The term **soil texture** refers to the size of the individual mineral particles. Soil particles have been classed according to size, as shown in Table 1. Textural designations are also used to describe soils (Fig. 1). The main ones are sand, silt, clay, and loam. The nontechnical terms "lightness" and "heaviness" refer to soil texture. "Heavy soils" are high in clay and other fine particles; "light soils" are low in clay and high in sand and other coarse particles.

The coarse materials such as sands and gravels are usually composed of many small particles cemented together either chemically or by a matrix material. These are bound relatively firmly and present only a single outer surface. The physical and chemical properties of these coarse materials do not differ greatly from those of their parent materials.

Silt particles, which are smaller than sand particles, are more or less unweathered, but their surfaces are coated with a clayey matter. The properties of silt are therefore somewhat intermediate between those of sand and clay.

Table 1. Classification of soil particles.[1]

Particle	Diameter (mm)
Coarse sand	0.5–1
Medium sand	0.25–0.5
Fine sand	0.1–0.25
Very fine sand	0.05–0.1
Silt	0.002–0.05
Clay	<0.002

[1]The International Classification (Atterberg) System refers only to soil particles under 2 mm:

Coarse sand	0.2–2 mm
Fine sand	0.02–0.2
Silt	0.002–0.02
Clay	<0.002

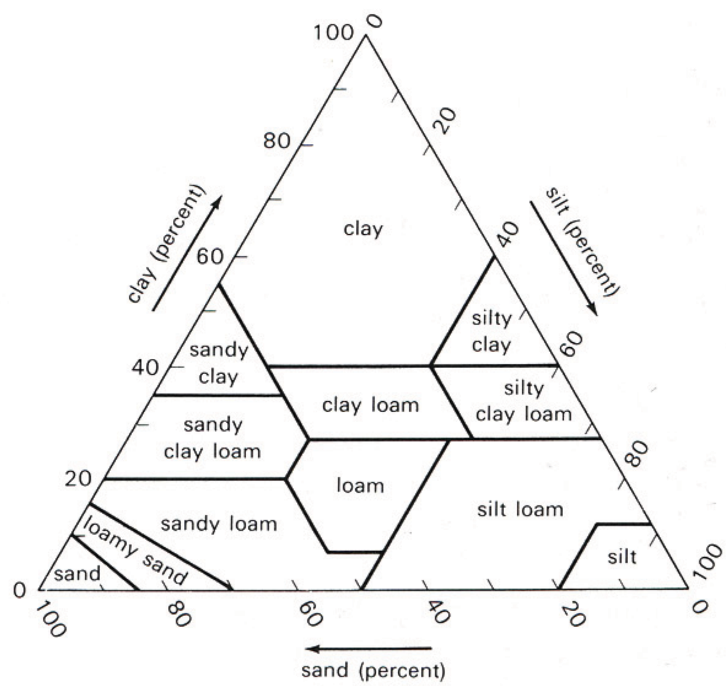

Fig. 1. The soil-texture triangle shows the relative percentages of sand, silt, and clay in each textural class. (In the United States, the term "loam" refers to a soil with more or less equal proportions of sand, silt, and clay. As used in Great Britain, the term refers to a soil high in organic matter, a "mellow" soil.) [Courtesy USDA.]

The clays, the smallest of the soil particles, show distinct chemical and physical properties. Clays are colloidal*—they are viscous and gelatinous when moist but hard and cohesive when dry. Their structure can only be seen with an electron microscope. Clays are composed of particles called **micelles**, which are formed from the parent materials by a crystallization process; they are not merely finely divided rock. The micelles are sheetlike (laminar), with internal as well as external surfaces, and tend to be held together by chemical linkages or ions between the plates. Their tremendous surface area relative to their volume is one of their most significant features.

The structure of clay micelles may be complex (Fig. 2). Clay particles are negatively charged and thus attract, retain, and exchange positively charged ions. The adsorbed water on clay parti-

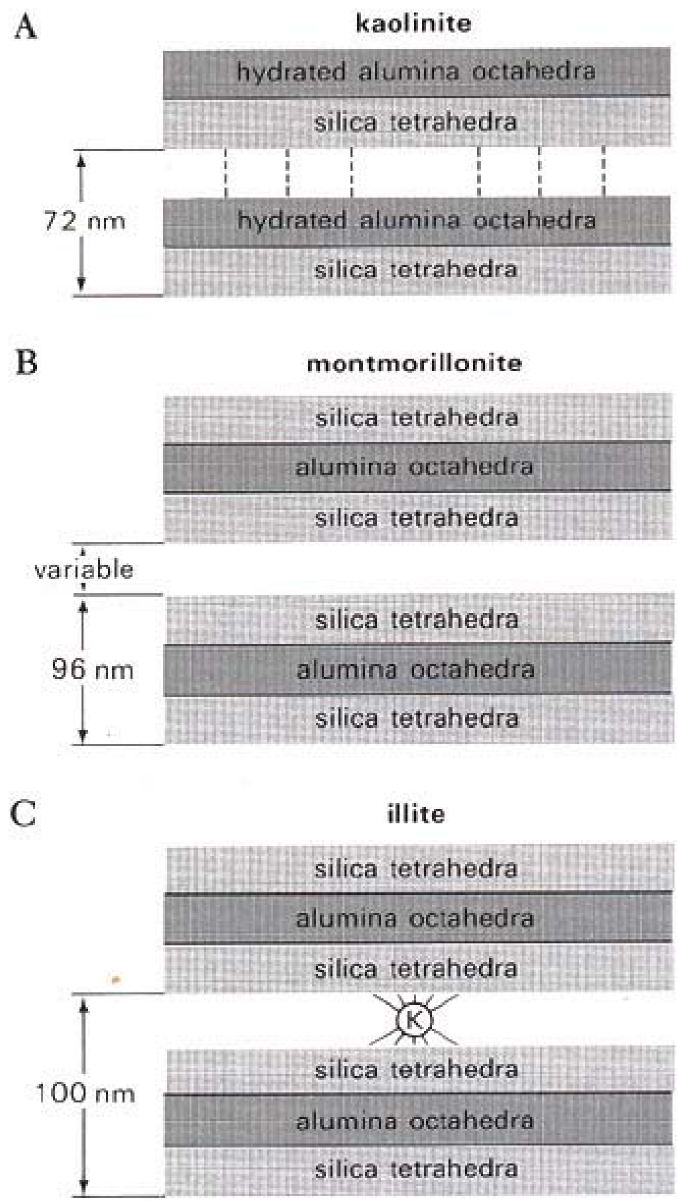

Fig. 2. The crystalline structure of clay. (A) The simplest clay mineral is called kaolinite. The micelles of kaolinite consist of two different layers, one of silica and the other of alumina. Kaolinitic clay micelles are relatively large and are bound together tightly. The distance between the alumina and silica layers is rigidly fixed and does not increase when water is adsorbed on the surfaces of the individual micelles. The internal space is not available for surface reactions. Such clays do not shrink greatly when dry or expand much when hydrated. (B) Montmorillonite is more complex, and each micelle consists of an alumina layer sandwiched between two layers of silica. These clays are not bound together tightly, and they swell when wet because the hygroscopic surfaces between layers adsorb water and force the layers apart. All surfaces can adsorb water and minerals. (C) The micelles of illite consist of an alumina layer between silica layers, and adjacent layers are held together by potassium atoms. Surface adsorption can take place on the surfaces between crystals to a limited degree. Illite is less abundant than kaolinite or montmorillonite.

*A colloid is a small, insoluble, nondiffusible particle larger than a molecule but small enough to remain suspended in a fluid medium without settling. Most soils contain organic colloidal particles as well as the inorganic colloidal particles of clays.

cles acts both as a lubricant and as a binding agent. Clay platelets behave like a stack of wet poker chips. This to a large degree explains the plasticity of clay. Wet clay soils low in organic matter and low in weakly hydrated cations, such as calcium, become sticky or puddled. The unique chemical and physical properties of clays are responsible for most of the important properties of soils.

Soil texture affects the retention of water and the rate of water infiltration. Coarse soils permit the rapid infiltration and percolation of water, so that there is no surface runoff even after a heavy rain. In contrast, clay soils are so finely textured that very little water penetrates to lower levels, especially after the surface clays become wet and expand. Coarse soils, however, are incapable of retaining large amounts of water. The range of capacity for holding moisture available for plant growth among soils of different textures is given in the following tabulation:

Texture	Soil type	Water capacity (mm/m soil)
Very coarse	Very coarse sands	33–63
Coarse	Coarse sands, fine sands, and loamy sands	63–104
Moderately coarse	Sandy loams and fine sandy loams	104–146
Medium	Very fine sandy loams, loams, and silt loams	125–192
Moderately fine	Clay loams, silty clay loams, and sandy clay loams	146–208
Fine	Sandy clays, silty clays, and clays	133–208
Peats and mucks		167-250

Soil Structure

Soil structure refers to the gross arrangement of the soil particles into aggregates. A soil may have either a simple or a compound structure. Sands and gravels, examples of soils with a **simple structure**, have very little cohesion, plasticity, and consistency (the resistance of the particles in the soil to separation. Simple-structured soils are usually composed of materials that are relatively resistant to weathering, such as quartz sand. They, are also said to have a **single-grain structure**.

Most agricultural soils have a **compound structure**; their particles aggregate, or stick together. Several distinct sizes of compound structures are recognized.

Structural type	Aggregate diameter (mm)
Columnar	>250
Blocky	5–25
Granular	3–5
Crumbly	1–3
Massive	Completely puddled or compacted

Soil structure develops when small colloidal soil particles clump together or **flocculate** into granules. Granulation is promoted by freezing and thawing, the disruptive action of plant roots, the mixing effects of soil fauna, the expansion and contraction of water films, and the presence of a network of fungal hyphae. However, unless the granules are stabilized by coatings of organic matter or by their own electrochemical properties, they will coalesce into clods.

Good soil structure is very important for agricultural soils. Highly granulated soils are well aerated and have a high water holding capacity because of the increased volume of the soil pore space. The **pore space** of soil is occupied by water and air in varying proportions, the soil acting as a huge sponge. The total pore space of soil, which is typically about 50% of the total volume, is not as important as the size of the individual pores. Clay soils have more total pore space than sandy soils, but because of the small size of the pores in clay soils, air and water move through them slowly. When the small pores of clay soils become filled with water, aeration is greatly limited. Large pore spaces become filled and are drained by gravity, whereas small pores absorb and retain water by capillary action. Capillary water is of the utmost importance to the plant: it is the soil solution most used by plants.

The crumbly nature of good agricultural soils depends on soil texture and on the percentage of humus (decomposed, stable organic matter). Clay soils low in organic matter typically have poor structure. In order to maintain good compound structure in clay soils, they must be carefully managed. If worked when too wet, the structure may be damaged (Fig. 3). When clods are exposed they become dry hard, and difficult to work back into the soil. In heavy soils it is necessary to add organic matter to maintain good structure. In sandy soils, where structure is not as critical, it is necessary to add organic matter to increase its water and nutrient-holding capacities.

Exchange Capacity

The capacity of a soil to retain and exchange such cations as H^+, Ca^{2+}, Mg^{2+}, and K^+, is called its **exchange capacity**. Exchange capacity, a measure of the chemical reactivity of the soil, varies inversely with particle size (Fig. 4). Because a given volume of small soil particles has much more surface area than an equal volume of large particles, fine soils accumulate and retain many times more cations than do coarse soils. The soil's colloidal particles, clay and humus, are negatively charged and attract cations. When these particles in a soil are saturated with hydrogen ions, the soil has a strong acid reaction.

The exchange capacity of the soil's colloidal particles is of tremendous importance. Nutrients that would otherwise be lost by leaching are held in reserve and when exchanged become available to the plant.

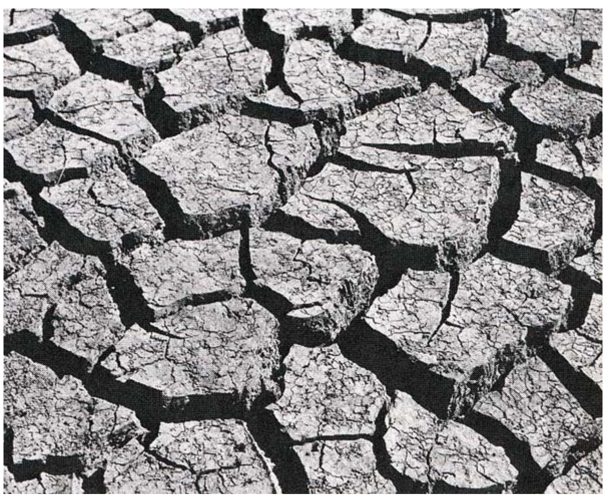

Fig. 3. Puddled clay soils may form large cracks when they dry out. This condition indicates an unproductive soil that has been poorly managed. [Courtesy USDA.]

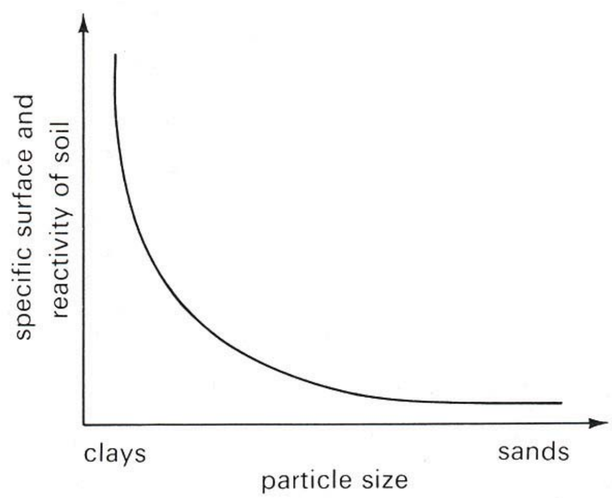

Fig. 4. The reactivity of soils depends on the total surface area of the soil particles per unit volume of soil. The total surface area varies inversely with particle size. [Courtesy USDA.]

The process of cation exchange is not a random one. Cations differ in their ability to replace one another; if present in equal amounts,

H^+ replaces Ca^{2+} replaces Mg^{2+} replaces K^+ replaces Na^+.

If one cation is added in large amounts it may replace another by sheer force of number (mass action). This is largely what occurs with the addition of fertilizer.

The release of hydrogen ions in soils tends to promote the exchange of cations, making them available to plants. Hydrogen ions are made available by the dissociation of carbonic acid formed from the carbon dioxide released by roots and from the even larger amount released by the enormous population of microorganisms in respiration and in the decomposition of organic matter:

$CO_2 + H_2O = H_2CO_3 = H^+ + HCO_3^-$

The cations are replenished by the decomposition of the inorganic fraction of the soil, by the degradation of organic materials, and by the application of fertilizer. The cations in a productive soil are in equilibrium between the soil particle, the soil solution, the soil microorganisms, and the plant.

The cation exchange capacity of a soil is expressed in milliequivalents (meq), of H^+; that is, the number of milligrams of H^+ that will combine with 100 grams of dry soil. The exchange capacity of a soil depends on the percentage of humus it contains and on the percentage and composition of its clays. Clays differ markedly in their ability to exchange cations. Kaolinite has an exchange capacity of 10 meq/100 grams, whereas montmorillonite clay has an exchange capacity of about 100 meq/100 grams. The exchange capacity of humus ranges from 150 to 300 meq/100 grams. The ranges of exchange capacity for various soils are given in Table 2.

The ability of a soil to supply mineral ions for absorption by plants is a measure of its **fertility**. It is quite possible for soils to contain relatively large amounts of minerals and yet be infertile because the ions are unavailable to plants. In a region with moderate to large amounts of rainfall, simple soils are usually exceedingly low in fertility because minerals are readily lost by leaching. Such crops as peanuts, which are grown in sands, must be fertilized frequently and carefully.

Soils may be fertile without being **productive**. Some desert soils have an exceedingly high natural fertility but must be irrigated to render them capable of producing crops. A fertile soil can be productive only when moisture, temperature, and other environmental factors are in good balance. The aim of soil management must be to make maximum use of the productive capacity of the soil.

Soil Organic Matter

Soil organic matter is the fraction that is derived from living organisms. Most apparent is the **litter** on the surface. It is composed of undecayed leaves, branches, reproductive parts, and other

Table 2. Ranges of cation exchange capacity for various soil types.

Soil type	Cation exchange capacity (meq/100 g)
Sands	2–4
Sandy loams	2–17
Loams	7–16
Silt loams	9–26
Clay and clay loams	4–60
Organic soils	50–300

residues from the top parts of plants. **Duff** refers to partially decayed litter. It is frequently matted together with fungal mycelia, and in this condition it is called **leaf mold**. Duff forms when soil is moist enough to supply the water essential for microbial activity and when litter is thick enough to prevent evaporative water losses. Leaf mold is an important component of forest soils, but it is never found in cultivated agricultural soils. Plant roots and the excreta, sheddings, and bodies of soil organisms, although not as apparent, also contribute to soil organic matter.

The upper layers of the soil are often high in an organic fraction called **humus**. Humus is relatively resistant to further breakdown and decomposition. Humus, unlike mineral colloids, is noncrystalline. The primary sources of humus in the upper soil layers are surface litter and plant roots. As surface litter is broken down by mechanical action and decomposed into fine particles by microorganisms, it is washed down into the soil, where it becomes a part of the soil complex. The washing action can only affect the surface of most soils. The decomposition of dead roots provides organic matter throughout the upper soil. Prairie soils, which receive small amounts of precipitation, have a low rate of biological decomposition, so that organic matter from dead grass roots accumulates to make them dark in color, friable, and extremely fertile.

Perhaps one of the most important contributions of organic matter to soil is its water-holding capacity. Organic matter acts like a sponge: it can absorb large amounts of water relative to its weight. Because it is porous, it also readily permits the infiltration of water. Organic matter is also a source of mineral elements, which are made available when it decomposes. The decomposition by bacteria, fungi, and other organisms of organic matter to form water and carbon dioxide with the release of minerals is called **mineralization**. This is an important aspect of **chemical cycling** in stands of vegetation. Chemical cycling consists of (1) the absorption of minerals through roots and their incorporation into chemical compounds of various kinds in plants, (2) the death of plants and plant parts, (3) and the decomposition of the plant material and the release of its contained minerals into the soil. The minerals are then reabsorbed and recycled. The high adsorptive capacity of organic matter is also important in the retention and exchange of mineral cations. When organic matter decomposes or when fertilizers are added to the soil, the mineral elements made available are subject to leaching. Organic matter may retain large quantities of minerals and thus prevent their losses from the soil. Organic matter may account for as much as 90% of the absorptive and adsorptive capacities of sandy soils.

Organic matter helps maintain the structure of cultivated soils. Finely divided organic matter covers mineral particles and keeps them from sticking together. Clay soils with an appropriate quantity of organic matter are less inclined to be sticky and are more readily cultivated. Crop growers say that soils that are friable and easy to cultivate have good **tilth**.

Soils are frequently classified according to their content of organic matter. One such classification is as follows:

Soil name	% Organic matter
Mineral	0–10
Muck	40–50
Peat	40–100

Although most agricultural soils are mineral soils, mucks and peats may also be rendered extremely productive under proper management. Mucks and peats develop when organic matter from living plants is covered by water and does not decompose. Once these soils are exposed to air by cultivation and drainage, bacteria and fungi begin to decompose them, with the result that the soil surface is actually lowered. In the Florida Everglades, drained and cultivated peat soils actually subsided nearly 2 meters (about 6 feet) during 40 years of cultivation (Fig. 5).

Soil Organisms

Soil organisms play an important part in soil development. In addition to the roots of higher plants, the soil is inhabited by a wide variety of plant and animal life (Fig. 6). In fact, a soil does not usually develop until the inorganic material is "invaded" by various kinds of organisms. The total weight of soil organisms (excluding higher plants) in the upper 30 centimeters (about 1 foot) of fertile agricultural soils is impressive, as much as 7000 kilograms per hectare (about 6250 pounds per acre), which is equivalent to the weight of 20 to 30 marketable hogs (Table 3). This is, however, only about 0.1 percent of the weight of the soil that the organisms occupy.

Higher plants must be considered the principal soil organisms. Roots of trees and other higher plants penetrate crevices in rock, expand them, and split the rocks by the tremendous forces they exert when growing, thereby performing an important function in the continuing process of soil formation. Roots exude many kinds of organic acids and other substances that hasten the solution of soil minerals and make them available to plants. Living roots give off CO_2, which raises

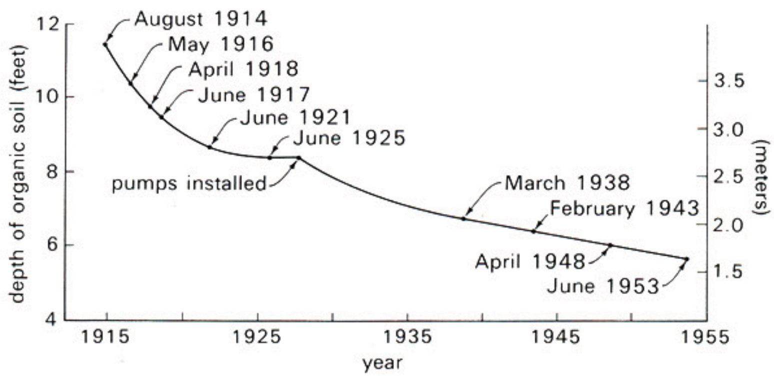

Fig. 5. The subsidence of drained organic soils in Florida over a period of 40 years. Gravity drainage began in 1914. It was necessary to install pumps for drainage in 1927 in order to keep surface soils dry enough for cultivation. [Courtesy USDA.]

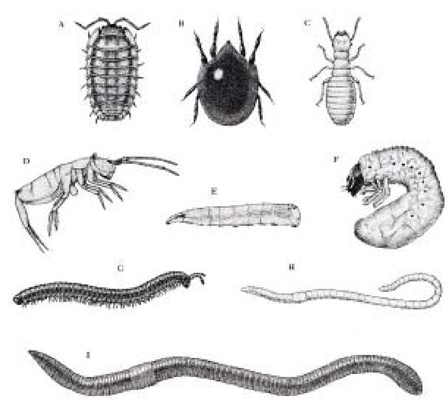

Fig. 6. Nine small animals are responsible for the fertility of most forest soils. They include the wood louse (A), the oribatid mite (B), the termite (C), the springtail (D), the fly larva (E), the beetle larva (F), the millipede (G), the enchytraeid worm (H), and the earthworm (I). [From C. A. Edwards, "Soil Pollutants and Soil Animals."]

Table 3. Average weight of organisms in the upper 30 centimeters of soil (in kilograms/hectare).

Organism	**Low**	**High**
Bacteria	560	1120
Fungi	1680	2240
Actinomyces	895	1680
Protozoa	225	450
Algae	225	335
Nematodes	28	55
Other worms and insects	895	1120
Total	**4508**	**7000**

the carbonic acid content of the soil solution and increases the rate at which soil minerals dissolve. When leaves fall, or when plants die, their organic matter becomes incorporated into the soil, contributing to its fertility. Channels remaining after dead roots have decayed serve as pathways for the movement of soil water.

Bacteria are present in all soils. Estimates of the weight of living and dead bacteria in forest soils have been as great as 6300 kilograms per hectare (about 5600 pounds per acre), whereas fertile agricultural soils typically contain less than 20% of this.

Bacteria in the soil decompose organic matter produced by plants (and other organisms), releasing the minerals they contain, which then become available for another cycle of plant growth. Some kinds of bacteria, such as those in the genus *Azotobacter*, convert molecular nitrogen from the atmosphere into nitrogenous compounds that can be used by plants. Other species live in symbiotic association with the roots of certain kinds of plants and perform the same function. **Nitrogen-fixing bacteria** supply nitrogen to the plant while the plant supplies carbohydrates to the bacteria. Some bacteria play roles in soil formation and degradation, but these processes are poorly understood.

Not all soil bacteria are helpful. Many species are **pathogenic**, causing crop diseases and large economic losses. Other harmful types oxidize ferrous iron to the slightly soluble ferric form, thereby contributing to the formation of soil horizons called **hardpans**, which are extremely rich in iron and quite hard. Hardpans may prevent the drainage of excess water and inhibit root penetration.

Fungi perform many of the same functions that bacteria carry out in decomposing organic matter and in cycling nutrients. Many soil-borne fungi are also pathogenic. **Saprophytic fungi** decompose the dead organic matter of soils. When temperature, moisture, oxygen, and soil acidity are in the right balance, these fungi decompose protein and cellulose, lignin, and other carbohydrates, changing them to humus. Even the bark of trees, which is highly resistant, is decomposed by fungi.

Many species of fungi live in such close symbiotic association with roots (particularly of woody plants) that organic and inorganic materials pass back and forth. Such an association is known as a **mycorrhiza**. Water and minerals move from the fungi to the roots, and carbohydrates and other organic materials move in the other direction. Some mycorrhizal fungi actually penetrate the interior of the roots; others remain on the outside. The importance of these fungi is becoming increasingly apparent. Most species of pines cannot survive without them, and there is increasing evidence that they may be associated with the roots of practically all plant species.

Most types of algae are aquatic, but several kinds, mainly the blue-green algae (division Cyanophyta) and the green algae (division Chlorophyta), are also found in the soil, where they hasten the weathering of soil minerals. Algae normally occur near the soil surface, as they require light for photosynthesis. **Lichens** are made up of an alga and a fungus living in a symbiotic relationship. They occupy a special niche in the process of soil formation. They become established on rocks, which they very slowly dissolve, and also serve as traps for dust, which accumulates and may form the soil in which other plants become established. Organic acids are leached from living and dead lichens, increasing the rate of solution of the rocks to which they are attached. In making possible the growth of other plants, lichens hasten their own demise, for they soon become covered with litter and die.

Arthropods (phylum Arthropoda) are among the more obvious soil fauna. Into this large phylum fall the crayfish (important in poorly drained areas of the southeastern United States) mites, ants, centipedes, millipedes, sow bugs, insects, and numerous other species that physically cultivate the soil and contribute to its organic matter when they die. They are numerous and have a short life span and thus contribute to the soil hundreds of kilograms of organic matter per acre.

Ants, in particular, cultivate great amounts of soil. In parts of Germany, the red wood ant has been introduced into many forests to compensate for centuries of soil degradation due to timber cutting. Ants also loosen and aerate the soil and destroy many kinds of insects that are harmful to plants. Many ants and termites are severe pests in tropical areas. The large termite mounds in Brazil seriously interfere with cultivation. The leaf-cutting ant is one of the most destructive of tropical pests. Mites and myriapods play an important role in the breakdown and decomposition of forest litter.

The segmented worms (phylum Annelida), commonly called earthworms, and round nonsegmented eelworms, or nematodes (class Nematoda of the phylum Aschelminthes), are both important in agricultural soils. An early study of earthworms by the famous biologist Charles Darwin concluded that about 0.25 to 0.5 centimeters (0.1 to 0.2 inches) of subsurface soil may be brought to the surface each year by earthworms and deposited as castings. Nematodes are economically important because some of them are pathogenic to crop plants and others distribute parasitic fungi and increase the extent of root-rot diseases. Some species kill bark beetles and other insect pests; some give rise to serious disorders in mammals and birds.

A number of vertebrate animals, including many species of burrowing mammals, must be considered part of the soil fauna. Their effect is mainly one of cultivation, although their excrement contributes organic matter to the soil. Some, however, also destroy crops. Badgers, gophers, moles, voles, foxes, shrews, mice, ground squirrels, woodchucks, and even some species of birds, such as woodcocks, frequent the soil for all or a part of their lives. When present in great numbers they may become serious pests. Moles, for example, do considerable damage to turf grasses and certain farm crops. Beavers, through their dam building over the millennia, have had a profound impact on the forest soils of boreal areas.

Soil Atmosphere

The soil atmosphere exists in the pore spaces that are not filled with water. These pores contain the same gases as the atmosphere above the ground, but in different proportions. The soil atmosphere is not necessarily a continuous system, for there may be isolated, unconnected pore spaces.

The humidity of the soil atmosphere is near 100% much of the time. The carbon dioxide content of the soil is greater than that of the air above it because of the decomposition of organic matter, and it increases with depth because carbon dioxide diffuses very slowly into the air above the soil. Conversely, the oxygen content of the soil atmosphere is less than that of the air above the soil, and it decreases with depth. Oxygen in the soil is used in respiration carried on by roots and microorganisms, and is slowly replaced by diffusion from the atmosphere.

As water is added to a soil, the air in the soil is squeezed out. Consequently, plant roots may be deprived of oxygen in flooded or very wet soils. For some plants even a few days of flooding may be disastrous, especially during the growing season.

Perhaps one of the most characteristic features of the soil atmosphere is its variability. Because the distribution of dead roots, living roots, and microorganisms and the structure of the soil are not uniform, the rates of gas production and rates of exchange with the atmosphere are not equal, and show great seasonal variation. Conditions in cultivated agricultural soils are likely to be much more uniform than in forest soils.

Soil Moisture

Soil moisture includes free water as well as capillary water, hygroscopic water, and water vapor.

SOIL ORIGINS

Soil is formed as a result of all the interacting forces that affect the parent rock materials, air and water movement of particles, and the composition and fate of living organisms that inhabit it. Although much has been written about the fascinating subject of soil genesis, only a few of the most important contributing factors can be considered in this brief discussion.

Parent Materials

The **parent materials** of soils are the rocks or unconsolidated materials from which the mineral components of soils have been derived. The parent materials determine the physical and chemical properties of soils. The wide variety of soils found within relatively small areas frequently reflects a diversity of parent materials. **Residual materials** are formed by the weathering of rocks that have not been moved from the place where they were formed. **Transported materials**, which are often more important than residual materials, are those that have been moved to the place of soil formation by wind, water, gravity, ice, or a combination of these forces. When the Pleistocene glaciers were growing in size and moving southward in the Northern Hemisphere, great quantities of rock and other materials were scooped up on the front edges of the ice sheets and were deposited at great distances from their sources when the ice melted. Locally, landslides deposit unconsolidated materials downslope, which later become the **colluvial** (gravity deposited) parent materials of soils. Soils deposited in the bottomlands along rivers are called **alluvial**.

The three main kinds of rocks are igneous, sedimentary, and metamorphic (see Table 4). **Igneous** rocks are formed when molten lava or magma solidifies. **Sedimentary** rocks are formed when sediments that have accumulated in water or have been deposited from the air are compressed and cemented into rocks. **Metamorphic** rocks are formed when igneous, sedimentary, or previously metamorphosed rocks are altered and recrystallized by heat or pressure, or occasionally infiltrated by solutions of minerals that subsequently precipitate.

Weathering and Soil Formation

Chemical Processes

Many changes take place in the weathering of parent materials, both on the surfaces of rocks and within them. The main chemical processes are hydrolysis, carbonation, oxidation, and hydration.

Hydrolysis is a decomposition process in which water is one of the reacting agents. It can be illustrated by the hydrolysis of orthoclase feldspar (potassium aluminum silicate) by carbonic acid and water to produce kaolinite, an important clay mineral:

$$2\ KA1Si_3O_8 + H_2CO_3 + H_2O \text{ — } A1_2Si_2O_5\ (OH)_4 + K_2CO_3 + 4\ SiO_2$$

Table 4. Representative types of rocks of different origins.

Igneous	Sedimentary	Metamorphic
Basalt	Chalk	Gneiss (from granite)
Granite	Conglomerate	Marble (from limestone or chalk)
Obsidian	Limestone	Quartzite (from sandstone)
Pumice	Sandstone	Schist (from micaceous shales)
Rhyolite	Shale	Slate (from shale)

Carbonation may be illustrated by the decomposition of calcite (calcium carbonate) to calcium bicarbonate:

$CaCO_3 + CO_2 + H_2O — Ca(HCO_3)_2$

Calcium bicarbonate is highly soluble and is readily leached from soils.

Oxidation involves the loss of electrons to a receptor, which is frequently oxygen. Iron is a familiar substance that is easily oxidized. Iron pyrite is an important soil mineral that is oxidized to yield a hydrated iron oxide and sulfuric acid:

$4FeS_2 + 10H_2O + 15O_2 — 4FeO(OH) + 8H_2SO_4$

Hydration is the combination of molecular water with a compound. In the hydrated form it may be more subject to weathering processes. The mineral anhydrite (calcium sulfate) is hydrated to gypsum (hydrous calcium sulfate) by the addition of water:

$CaSO_4 + 2H_2O — CaSO_4 \cdot 2H_2O$

Temperature

Temperature is important in the weathering of parent materials because changes in temperature cause differential expansion and contraction of minerals and rocks. Since rocks are aggregates of minerals, each of which has a different coefficient of expansion, changes in temperature result in internal stresses that cause cracks. Even large boulders can be rent asunder by relatively small changes in temperature.

In rocks exposed to solar radiation, a very large temperature gradient is established within the first few millimeters beneath the surface. When this happens, the hot outer surfaces may expand and flake off (**exfoliate**). American Indians and members of other native cultures used the same principle to fashion arrowheads by repeatedly dropping water on heated flint on the spot where a chip was to be removed.

Low temperatures cause water to freeze in the cracks of rocks and split them apart. When water freezes it exerts a force of about 1465 metric tons per square meter (150 tons per square foot). Freezing is probably the main weathering agent at high latitudes and altitudes. The rubble formed by freezing has characteristic sharp edges.

The dissociation of water molecules into hydrogen (H^+) and hydroxyl (OH^-) ions is much greater at high temperatures than at low temperatures. Since H^+ ions are particularly effective in dissolving minerals, the rate of weathering is faster when temperatures are higher. If soil is frozen or very cold throughout the year, bedrock may be weathered only a few centimeters deep. On the other hand, weathering in the tropics may extend to a depth of 50 meters (more than 160 feet).

Rainfall

Soil moisture is obtained in most areas through rainfall, although fog and dew are important in some parts of the world. The pounding of raindrops over thousands of years plays an important role in the weathering of exposed rocks and in the erosion of weathered materials. Such effects are minor, however, when compared to the effects of soil moisture in leaching dissolved minerals and providing a medium in which soil chemicals react to form complex compounds of many kinds. And these effects in turn are minor when raindrop joins raindrop to form streams, which erode and grind away mountains of material, redistributing them hither and yon.

Rainfall is frequently the most important climatic element in soil development. In regions of moderate to high rainfall, soil development is likely to be greater than in those where rainfall is sparse. Desert soils are usually poorly developed, yet, in adjacent areas with adequate rainfall to sustain plant growth, soils originating from identical parent materials may be well developed and productive.

Topography

Topography frequently plays an important part in soil development. If the land is flat, low, and poorly drained, water may accumulate and drain so slowly that biological activity will be arrested for long periods. Under such conditions, soil material, both inorganic and organic, may remain in a state of preservation until the land is drained. When topography is very steep, parent materials may be subject to erosion by water, wind, and ice to such an extent that soil material is removed from the site as soon as it is weathered from the parent material. The most favorable topographic situation for soil development is one in which the slope is steep enough to carry off excess water, but not so steep as to permit the removal of weathered materials that lack the protection of a vegetative cover. In addition, for the development of "normal soil" the water table should be below the weathered parent material so that roots can occupy it to the greatest possible extent.

Time

The factors that contribute to the development of soil are straightforward. They fall into a discrete pattern of events. Yet, unless the time element in soil formation is recognized, the significance of the events that take place cannot be truly appreciated. A mature soil is not formed in a decade, or even 10 decades, but over thousands of years. Soil development and vegetational succession are related processes. When vegetational development reaches a **climax condition**, in which the vegetation type is in balance with its environment and is relatively unchanging, the soil will also have reached full development and will be in balance with its environment. The soil is then said to be **mature**. There is a large variation in the absolute length of time required for complete maturation. In the tundra of the far north, cold weather precludes rapid biological and physical weathering; consequently, 5 to 10 thousand years might be required to form a soil only a few inches deep. In the tropics, however, the much faster rates of reaction can lead to the development of soils that may be 5 to 10 feet deep in a much shorter period of time.

The age of a soil is determined by the degree to which it has developed toward maturity. It may be chronologically young (in terms of absolute years) and yet may be mature in terms of its zonal structure–the soil profile.

The Soil Profile

In excavating the soil to any appreciable depth, it is necessary to dig through distinct zones called **horizons**. The morphology of these horizons is called the **soil profile**. Each soil type has a distinctive profile that is determined by the particular combination of factors that produced the soil. By the time most forest and prairie soils are mature they have developed 3 major horizons, designated (from the top down) A, B, and C. The underlying bedrock (usually but not always the true parent material) is called the R horizon.

- The A horizon is the zone of leaching (eluviation). Roots, bacteria, fungi, and small animals (for example, earthworms and nematodes) are most abundant in this horizon. It is poor in soluble substances and has lost some clay and some iron and aluminum oxides.
- The B horizon is the zone of accumulation (illuviation). It is less abundant in living matter. It is higher in clay and in iron and aluminum oxides, and is thus stickier when wet and harder when dry.

- The C horizon consists of weathered rock material, often true parent material. When hardpans are present (as in prairie soils and the soils of wheat and corn raising regions) they are a part of this horizon.
- The R horizon is the underlying consolidated bedrock, such as limestone, granite, or sandstone, from which the overlying horizons were formed.

Often it is desirable to subdivide the A or B horizons further. They are then each divided from top to bottom into 3 strata: A_1, A_2, and A_3; B_1, B_2, and B_3. The A_1 stratum is often dark in color, owing to its high content of organic matter. The middle stratum of a horizon (A_2 or B_2) is always the typical one for that horizon; the others tend to grade into their neighbors. The layer of partially decomposed duff immediately above the A horizon can be referred to as the A_0 horizon, and the fresh litter above that as the A_{00} horizon. Not all profiles show complete development, and soils that have been used for agricultural purposes for long periods of time are especially likely to be lacking in 1 or more of the uppermost horizons. Their most prominent feature is the plow horizon–the horizon that has been repeatedly disrupted by plowing, disking, and harrowing.

Soils with well-developed profiles are called **zonal**, or **normal soils**. Zonal soils are found where the factors of soil formation are conducive to profile development. **Azonal soils** have no distinct profile and are frequently alluvial (water deposited) or colluvial (gravity deposited) soils of recent origin. **Intrazonal soils** are those that are limited in extent and are under the control of a local factor, such as high salt content or poor drainage, that does not permit the development normally associated with zonal soils.

Some soils have been **truncated**. That is, they consist of only a portion of the original profile, the upper portion having been lost through erosion (Fig. 7). Most agricultural soils are truncated remains of the original soil that developed under natural vegetation, and some are completely new, having been formed by the addition of soil or organic matter from another location in order to increase productivity. At times, truncated soils are "buried" under soil deposited by wind or water (Fig. 8).

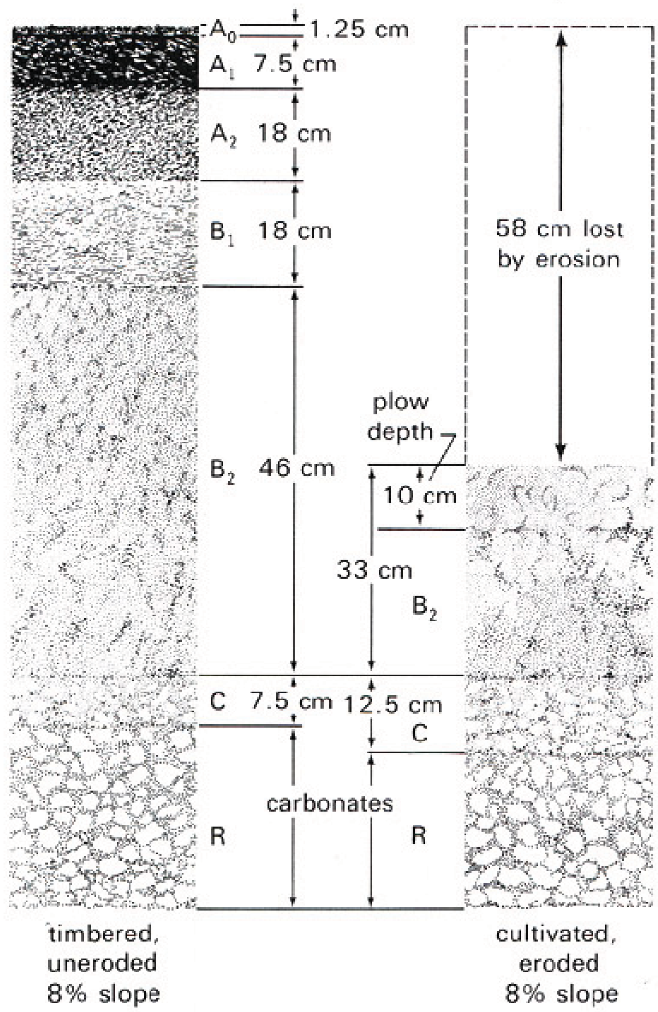

Fig. 7. Uncontrolled erosion can result in the loss of productive topsoil, as shown by these profiles taken in Miami silt loam on adjoining fields. The profile at the left was taken on a field still covered by virgin timber; the profile on the right was taken on a cleared field that had been farmed for 50 to 75 years. [Data from USDA.]

Reading 6

Major Soil Groups

Differences in soil-forming processes lead to different zonal soils. The major soil groups are based on climatic differences. In the humid regions 3 broad groups have been recognized: tundra, podzolic, and lateritic soils. In the arid and semiarid regions specific soils have developed in response to low rainfall. These include the chernozems, or black soils, and various desert soils.

The **tundra soils** are formed in cold climates, where biological activity is minimal. Organic matter accumulates on the surface, and the deeper horizons remain frozen throughout the year (permafrost). In winter, tundra soils are completely frozen. Their horizons are only poorly differentiated. These soils are of little agricultural significance.

In cold, humid climates a particular combination of soil-forming processes, collectively called **podzolization**, produces **podzolic soils**. **Podzols**, the most extreme type, have a deep accumulation of litter and humus, a strongly acid reaction, and an upper horizon from which iron and aluminum oxides (the so-called sesquioxides) have been leached. (The name "podzol" is derived from the Russian and means "ash beneath," with reference to the color of the A_2 stratum.) Fungi are the main soil forming organisms. True podzol soils are found at the higher latitudes and coincide with the boreal forest. The mild summers and long, cold winters in these latitudes permit the accumulation of the litter and humus necessary for their formation. Even in temperate climates, however, and sometimes under special conditions in the subtropics, podzolization is a factor. The widespread forests of the temperate zone grow predominantly on podzolic soils. They are potentially good agricultural soils, topography permitting, but they are easily degraded by poor cropping practices.

In the humid tropics and subtropics the combination of soil forming processes is collectively called **laterization** and forms **lateritic soils**. **Laterites**, the extreme type, have a very shallow accumulation of litter and humus, a neutral soil reaction, and an accumulation of iron and aluminum oxides in the upper horizons. Bacteria are the primary soil forming organism. Laterites are typical of tropical rain forests, and are characterized by extremely intensive chemical weathering. Even the most resistant compounds, such as silica, are broken down and leached by the heavy precipitation in the tropical rain forests. These soils are so deeply weathered that some geologists regard laterization as a geologic rather than a soil-forming process. The name "laterite" is derived from the Latin word *later*, which means brick; these soils are widely used as building materials.

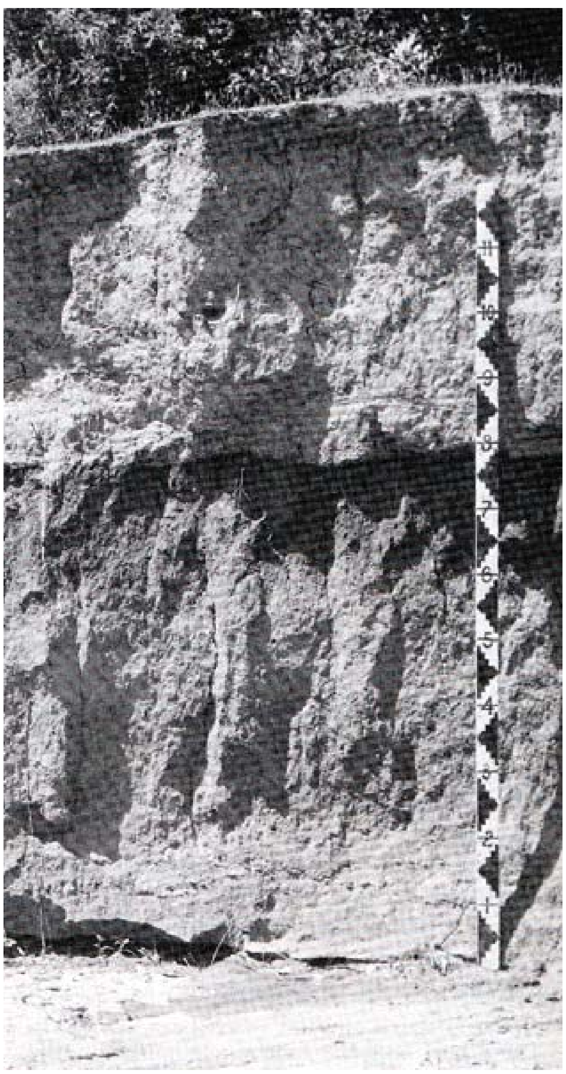

Fig. 8. Silt was deposited on a flood-plain soil, and a second soil developed from the silt. The soil whose former surface shows at the 8-foot level is called a buried soil. [Courtesy USDA.]

Some soils in climates with low precipitation accumulate carbonates on and near the surface. This process, called calcification, tends to produce very alkaline soils, which are characteristic of deserts and steppes.

Podzolization and laterization are compared in Table 5. Figure 9 shows the relation of all 3 soil forming processes.

Chernozems are formed in areas that receive 40 to 60 centimeters (15 to 25 inches) of rain per year. The natural vegetation is grass. The upper horizon is dark due to the accumulation of organic matter. Chernozem means “black soil.” In the temperate zones these are among the most fertile agricultural soils, and produce much of the world’s grain.

Desert soils are on1y slightly weathered and leached because of low rainfall. Nutrients other than nitrogen are present in moderate or large quantities. As a result, under irrigation and proper management these soils may become very productive.

Table 5. Comparison of podzolization and laterization in soil formation under optimal conditions.

Variable	Podzolization	Laterization
Climate	Cold	Warm to hot
Natural vegetation	Conifers	Tropical rain forest
Most active soil–forming microorganisms	Fungi	Bacteria
Raw humus	Abundant	Sparse
Soil reaction	Acid (pH 4–4.5)	Nearly neutral (pH 6.5–7)
Earthworms	Scarce	Abundant
Solubility of silica	Low	High
Iron and aluminum	Leached out of A horizon	Accumulate in A horizon
Hydrolysis	Weak	Intense

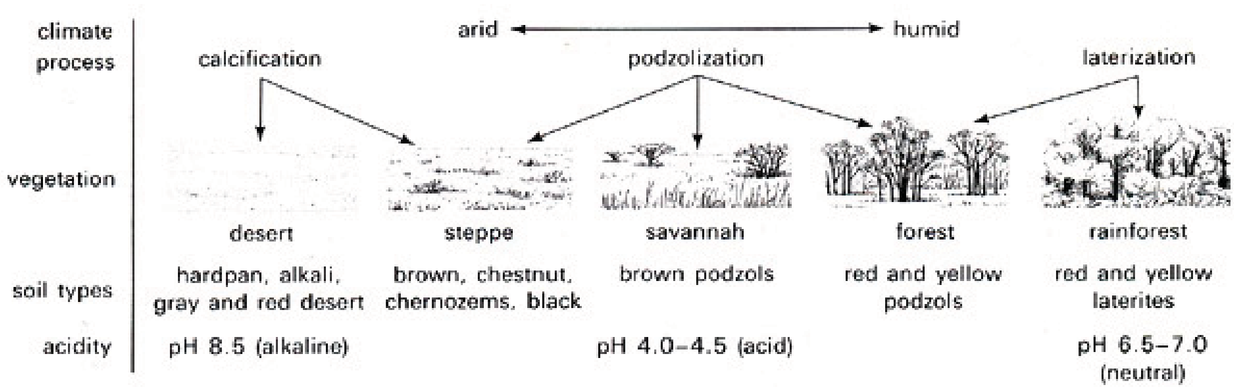

Fig. 9. The various soil-forming processes are not discrete. They form a continuum, so that some soils are the result of a combination of processes, while others are more clearly a function of a single process. [Courtesy USDA.]

SOIL CLASSIFICATION

Soils may be classified on the basis of genetic origin–that is, their parent materials–or on the basis of morphology. The National Cooperative Soil Survey initiated a new system called the United States Comprehensive System of Soil Classification, which contains 8000 soil series and about 80,000 soil types and phases. This system, which took 15 years to devise, does not alter the basic content or form of the soil survey report that soil conservationists and land use planners have used in the past. Neither does it require major changes in the technical guides for engineers, biologists, and other users of soil survey information. It does, however, permit a higher degree of accuracy in classifying soils, permit greater efficiency in mapping, and allow the classification of soils that for various reasons could not be included in other systems.

The classification system used previously was developed and published in 1936 by C.F. Marbut, who was chief of the U.S. Soil Survey at that time. A drastic modification, outlined in the 1938 Yearbook of Agriculture (*Soils and Men*) was used until 1965. The Comprehensive System differs from all other systems in 2 important respects: (1) the nomenclature of the higher categories is entirely new, and (2) definitions of the classes are much more quantitative and specific.

The new system emphasizes the properties of soils as they exist today. Previous classifications were based on assumptions of what the soil was when the country was settled, even though cultivation and erosion might have changed them greatly. It was always difficult to get agreement about the genesis of many soils. Thus, the new classification is much more utilitarian than the older ones.

A new language was created for the higher categories of classification so that there would be no confusion with names or words formerly in use. Soil scientists selected the diagnostic properties for each class, and classicists from the University of Illinois and the University of Ghent proposed Greek and Latin names for them.

In the new system there are 10 **orders** of soils, each defined by a few distinguishing characteristics (Table 6; Fig. 10). As an example, 1 of the orders is designated "Oxisol," the *oxi* referring

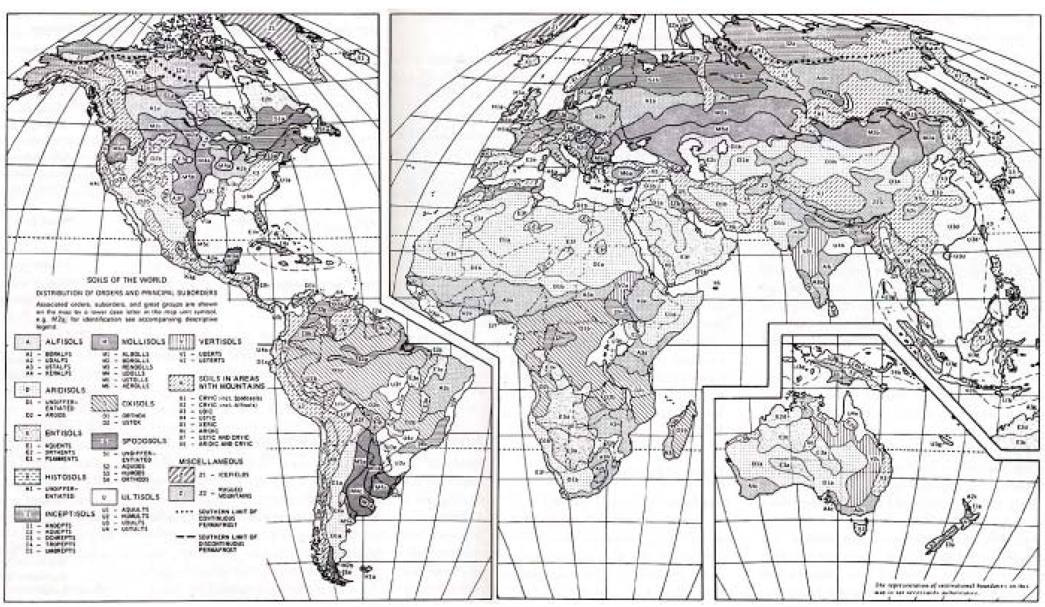

Fig. 10. Soils of the world: the distribution of the orders and principal suborders. [Courtesy USDA.]

Table 6. Soil orders according to the comprehensive system of classification.

Order	Formative syllable	Derivation	Meaning	Diagnostic features	Older equivalents
1. Entiso	ent	Meaningless syllable	Recent soil	Very weak or no profile	Regosols, lithosols, alluvial, some low humic gley
2. Verticol	ert	Latin: *verto*, turn	Inverted soil	Self–mulching; expanding lattice clays; subhumid to arid climates	Grumusol, regur, black cotton, tropical black clays, smonitza, some alluvial
3. Inceptisol	ept	Latin: *inceptum*, beginning	Young soil	Weak profile development but no strong illuvial horizon; cambic horizon present	Brown forest, subarctic brown forest, tundra, ando, and some lithosols, regosols, and humic gley
4. Aridisol	id	Latin: *aridus*, dry	Arid soil	Soils of arid regions; often have natric, calcic, gypsic, or salic horizons	Desert, red desert, sierozem, reddish brown, solonchak, some regosols, and lithosols
5. Mollisol	oll	Latin: *mollis*, soft	Soft soil	Thick, dark A_1 stratum; usually develops under grassy vegetation	Chernozem, brunizem (prairie), chestnut, red dish prairie, some humic gley, rendzinas, brown, reddish chestnut, and brown forest soils
6. Spodosol	od	Greek: *spodos*, wood ash	Ashy soil (podzol)	Illuvial horizon shows accumulation of iron and organic colloids; weak to strongly cemented hardpan	Podzols, brown podzolic, groundwater podzols
7. Alfisol	alf	Meaningless syllable	Aluminum–iron soil (pedalfer)	Argillic horizon of relatively high base saturation (>35%); usually under boreal or deciduous broad–leaf forest	Noncalcic brown, gray–wooded; many planosols, some half–bog soils
8. Ultisol	ult	Latin: *ultimus*, last	Ultimate (of leaching) soil	Argillic horizon of low base saturation (<35%); plinthite often present; humid climate; usually forest or savanna vegetation	Red–yellow podzolic, reddish–brown lateritic, rubrozem, some gley and groundwater laterites
9. Oxisol	ox	French: *oxide*, oxide	Oxide soil	Argillic horizon very high in iron and aluminum oxides	Latosols, and most groundwater laterites
10. Histosol	ist	Greek: *histos*, tissue	Tissue (organic) soil	Organic surface horizon (>30% organic matter) more than 6 inches thick	Bog and some half–bog soils

to oxide and *sol* to soil. These are the soils of tropical regions; they contain large amounts of iron and aluminum oxides.

Subcategories include **suborders**, **great groups**, **subgroups**, **families**, **series**, and **soil types**.

Suborders are named according to the distinguishing features of the horizons that develop. Thus, an "Aquox" is a wet soil, gray or bluish in color, with large amounts of oxides.

Great groups define the soils still more specifically, whereas suborders may make reference to minor properties that are also found in great groups. Families are based on properties important to the growth of plants.

The soil series is a collection of individual soils that are essentially uniform with respect to differentiating characteristics, including color, zonal development, and the depth limit within which each horizon is found. The series is classified according to type, the lowest category of classification based on texture.

Fortunately, the crop grower will still be able to call his soil by the same name as used before the advent of the new system. As a matter of fact, he need not even know that an old familiar soil such as "Lackland sand" is also an "ultic quarzopsamment!"

Land-Capability Classification The capability classification of land has been widely used in the United States. In this system, arable soils are grouped according to their potential productivity and their limitations for crop production without special treatment. Nonarable soils are grouped in 8 classes according to their risk of damage and their potential for sustained production. The first 4 classes are suitable for cultivation if good management practices are followed: Classes V through VII are not suited for cultivation, but can be used for grazing and forest management. Class VIII land is useful only for recreation, wildlife, and watersheds. Details of the classes are as follows:

- *Class I* soils are potentially the most productive of all soils. They are nearly level, and are not particularly susceptible to erosion. They are deep and well drained, with a good nutrient supply and water-holding capacity, and have all of the other physical and chemical characteristics required for intensive crop production. They can be used for the production of cultivated crops, pasture, range, forests, and wildlife. Irrigated soils may be placed in Class I if water is supplied by a permanent irrigation system.
- *Class II* soils have some limitations. They may have gentle slopes, moderate susceptibility to erosion, a soil depth that is less than ideal, slightly unfavorable soil structure, wetness that can be corrected by drainage, slight climatic limitations, moderate salinity or alkalinity, or other slight limitations. Farm operators have a smaller choice of crops to produce on these soils than they do on Class I soils. Class II soils can be used for crops, pasture, range, forests, and wildlife.
- *Class III* soils have severe limitations that reduce the choice of plants, frequently requiring the use of special conservation practices. They may have moderately steep slopes, high susceptibility to wind or water erosion, overflows that may result in crop damage, only slightly permeable subsoil, a shallow depth to rock or hardpan, which restricts rooting, poor fertility and moderate salinity or alkalinity, either all in combination or singly. They may be used for cultivated crops, pasture, forest, range, or wildlife. Management of these soils must be very good if they are to remain productive.
- *Class IV* soils have very severe limitations. They may be on steep erodible sites, have a history of erosion, be too shallow, be excessively wet, be severely alkaline, have a poor water-holding capacity, or be subject to damaging overflows. Although these soils may

be used for crops, pasture, forests, range, or wildlife, extremely careful soil conservation practices must be applied. It is not advisable to use them for crops that require extensive cultivation.

- *Class V* soils have little or no susceptibility to erosion, but they have other limitations such that they may be used only for pasture, range, forests, or wildlife production. They may be bottomland soils subject to frequent overflow, nearly level soils in areas where the growing season is short and limits the production of cultivated crops, level soils that are rocky, or ponded areas in which drainage is not feasible.
- *Class VI* soils have severe limitations. They may be steep, highly erodible or eroded, stony, shallow, wet, subject to overflow, saline, or alkaline, or they may have a poor water-holding capacity. They can be used for pasture, range, forest, or wildlife. Special practices, such as water control by contour ditches, water spreading, or drainage are usually necessary. Some of these soils are adapted to special crops such as sodded orchards and blueberries.
- *Class VII* soils have such severe limitations that their use is restricted to grazing, forest, or wildlife. They are more severely restricted than Class VI soils because it is impossible to compensate for or to correct one or more of their continuing limitations. They may be too steep, stony, erodible, wet, alkaline, saline, or deficient in some other manner.
- *Class VIII* soils are useful only for recreation, wildlife habitat, watersheds, or aesthetic purposes. They cannot be managed for crops, grasses, or trees. Uncorrectable limitations may include erosion or erosion hazard, wetness, stoniness, salinity or alkalinity, or poor water holding capacity.

Land-capability classification can be made more Specific by means of subclasses, which specify the limitations of the soils in a given class. Four subclasses are recognized:

- *Subclass e* soils have experienced severe erosion, or have a potential erosion hazard.
- *Subclass w* includes soils for which excess water is the dominant limitation. Poor drainage, overflow, and high water tables are likely to be problems.
- *Subclass c* consists of soils for which temperature and lack of precipitation are likely to be problems. This subclass contains soils for which climate is the only limitation.
- *Subclass s* includes soils having characteristics that restrict rooting. These soils may be shallow, stony, alkaline, or saline, they may have low fertility that is hard to correct, or they may have a low water-holding capacity.

The capability classification of land has been used in the past solely for agricultural purposes. However, land use planners and municipal officials are now beginning to realize that this system can be applied in many other fields as well, such as in planning the location of new subdivisions. For example, a shallow soil with an impermeable layer close to the surface would preclude the use of septic tanks and drainage fields.

SOIL CONSERVATION

Conservation means "careful use." The careful use of our soil resource is an obligation we have not only to ourselves but to future generations as well. This obligation has not always been acknowledged or acted upon. As early as 1894 Assistant Secretary of Agriculture Charles W. Dabney wrote, "Thousands of acres of land in this country are abandoned every year because the surface has been washed and gullied beyond the possibility of profitable cultivation" (Fig. 11). Unfortunately, nearly a century later, this statement holds true on an even larger scale!

Soil conservation has many meanings. For crop producers it implies a careful and intensive series of management practices involving plants and soils. In forests, soil conservation requires the use of logging practices that will not permit erosion, the regulation of grazing, and protection from uncontrolled fire. To others less concerned with growing crops, it may mean the stabilization either of sand dunes along a beach or of steep slopes by planting appropriate plant species.

The basis of agriculture is a layer of topsoil that averages less than 18 centimeters (7 inches) in depth over the earth's surface. This soil cannot be recklessly exploited indefinitely; it must be preserved and refurbished. Although the reduction of productive capacity through the loss of fertility and structure is considerable, the most serious problem is erosion. Nutrients can be artificially supplied, but the loss of topsoil cannot be so quickly or easily remedied. The loss of soil due to wind and water is a national problem. It contributes to silt-clogged rivers, alternate drought and flood, dust bowls, and poverty.

Erosion of the soil is a natural process influenced by climate, topography, and the nature of the soil itself. Where permanent and undisturbed plant cover exists, erosion is more or less gradual and in equilibrium with soil-forming processes. Accelerated erosion comes about in the absence of plant cover. Areas that are unable to support a permanent plant cover as a result of climate or topography undergo large scale erosion of the kind that carved the Grand Canyon. The accelerated soil erosion brought about by agricultural cultivation or overgrazing comes about largely through the action of water in humid climates and of wind in arid climates.

The maintenance of vegetative cover is basic to soil management. Vegetative cover retards erosion by cushioning the beating force of the rain (Fig. 12), increasing the absorptive capacity of the soil, and holding the soil against both water and wind. The soil cover increases the infiltration of water through the soil by preventing the clogging of the soil pores by fine surface particles. The techniques used for increasing soil cover include the increased use of sod culture, proper rotation, cover cropping, and mulching,

Fig. 11. Uncontrolled erosion eventually results in the complete loss of the soil resource, accompanied by poverty and misery. This tragedy has been commonplace in many parts of the world. [Courtesy USDA.]

Water erodes the soil by literally carrying it away. The carrying power of water increases with its speed and volume. The volume of excess water depends upon the amount of rainfall and the rate at which it is absorbed by the soil. The speed with which this water moves is directly related to the slope of the land and the amount of cover. Any technique that either increases absorption or reduces the speed of the runoff will help prevent soil erosion.

The absorptive capacity of soil may be increased by deep plowing, by increasing the amount of organic matter in the soil, or by increasing drainage. Thus the burning or removal of organic matter is a poor conservation practice. Where natural drainage is poor, tiling may be necessary to remove water and provide air. In some regions hardpans have to be periodically broken up with plows cutting as deep as 2 meters (more than 6 feet).

The control of erosion by reducing the speed of runoff may be accomplished in a number of ways. Most basic is contour tillage, in which plowing, cultivation, and the direction of the "row" follows the contour rather than the slope of the land (Fig. 13). This affects the speed and power the surface water attains and thus the ability of the tilled soil to absorb water. The use of intertillage or strip cropping, which alternates strips of sod and row crops planted along the contour, helps to slow runoff by interposing barriers with high absorptive capacity. The alternation of sod with row cropping serves to achieve the benefits of rotation. On steep slopes where greater amounts of surface water must be accommodated, the use of **waterways**—permanently sodded areas—facilitates water removal and minimizes erosion.

Where contour cultivation and strip cropping are not sufficient to check erosion, terraces constructed on the contour must be used. **Terracing**, an ancient practice, consists in cutting a slope into a number of level areas. Terraces appear as giant steps on the hillside. Although the steps of ancient terraces were made of stone, modern terraces are made by building low rounded ridges of earth across the sloping hillside. Terracing slows down the speed of surface runoff, and, although it is designed primarily to prevent erosion, it facilitates the storage of available water. Thus terracing is an important practice in areas of low rainfall and where the scarcity of arable land necessitates the exploitation of steep hillsides.

Some of the erosion caused by wind, especially on open prairies or plains, may be checked by planting windbreaks, one or more rows of trees or shrubs planted at right angles to the prevailing

Fig. 12. A stroboscopic photograph has caught the impact of a raindrop on moist soil, bursting upward and outward and carrying soil with it. [Courtesy USDA.]

Fig. 13. Water was held on this 6 percent slope for 36 hours after a 10-centimeter (4-inch) rain without washing out the corn. Nearby fields planted in strai ght rows up and down the slopes had to be replanted. [Courtesy USDA.]

winds. The effectiveness of a windbreak is local and is related to the thickness and the height of the trees. The maintenance of a permanent plant cover in conjunction with windbreaks effectively reduces wind erosion where it is a problem. On organic soils, rows of small grain may be used as temporary windbreaks to protect seedlings.

Cropping practices almost always result in the loss of soil, much more so for row crops such as potatoes and corn than for crops that provide a permanent soil cover. Until recently, soil losses from sloping cropland could be estimated only in relation to losses from level cropland. Scientists at the University of Tennessee, using data from experimental plots, devised an equation, which applies directly to Tennessee agricultural land, for predicting soil losses for a given field under different management practices. The following components make up the equation:

- *A = average annual soil loss*, in tons per acre, over the course of a period of years. It may not be valid for any one particular year.
- *R = rainfall factor*, the erosion potential in a given locality. This factor expresses the intensity of rainfall and its kinetic energy.
- *K = soil erodibility factor*, a reflection of soil structure, texture, organic matter, permeability, depth, and all of the other characteristics that influence the rate of soil erosion.
- *LS = length-and-steepness-of-slope factor*, an extremely important consideration: longer and steeper slopes have more erosion.
- *C = cropping-management factor*, the ratio of soil loss under a specific management system to losses under continuous fallow.
- *P = conservation-practice factor*, a value for conservation practices such as contour plowing and terracing, which reduce soil losses.
- *T = soil-loss tolerance*, the estimated average annual soil loss that can be tolerated in tons per acre if sustained economical crop production is to be achieved.

In the equation, A is computed (by multiplying the factors R, K, LS, C, and P) and then compared with the T value. One acre-inch of soil weighs about 150 tons. If the average soil-loss is 5 tons per acre per year, then 30 years would be required to erode 1 acre-inch of soil from a field that is being cropped. If this rate of loss is too high for a particular situation, then either additional conservation must be initiated or cropping practices must be changed.

"NO-TILL" AND "MINIMUM-TILL" AGRICULTURE

The first humans to plant a crop merely punched a hole in the soil with a sharp-pointed stick, dropped in a few seeds, and waited for their crop to grow. They were practicing no-till agriculture. *Minimum till* is a variation in which tillage is avoided in every possible operation.

It may seem strange that today we "moderns" are trying to use the same basic system to conserve soil, soil moisture, and energy–and are finding that it works. The dust storms in the winter of 1977 would have been less severe if no-till systems had been in wide use in the drought-stricken western part of the United States.

There are many variations of no-till agriculture:

1. Alternating Strips of meadow and no-till corn, sometimes called *sod cropping*
2. Planting in last year's crop residues without cultivation called *stubble cropping*
3. Following corn and fall-seeded small grain with a second crop of soybeans without cultivation, called *double cropping*
4. Broadcast seeding and fertilization by aircraft for a totally undisturbed soil
5. Interseeding legumes into grass pastures

6. Interplanting corn with small-grain cover crops.

These are only a few of the possible variants of the system, which was once limited only by imagination. Although no-till agriculture is practiced today primarily for ethical reasons, it will be practiced in the future largely for economic ones: Agricultural engineers have estimated that conventional land preparation and planting requires 51.5 to 65.5 liters of fuel per hectare (5.5 to 7 gallons per acre), but no-till agriculture requires only 2.8 to 22.5 liters of fuel per hectare (0.3 to 2.4 gallons per acre).

No-till agriculture is not universally applicable. Soils with low pH and those with low phosphorus cannot be used. The method cannot be practiced where perennial weeds (such as Johnson grass, nutsedge, and bermuda grass) are established. On the other hand, large-seeded broadleaf weeds, such as cocklebur, may be reduced by the elimination of tillage. Damage by above-ground insects may be more common with no-till agriculture. Some diseases, such as gray leaf spot of corn, have been intensified, but a few, including stalk rot of sorghum, have been reduced. Appropriate pesticides can help control these problems.

It is safe to say that no-till and minimum-till are in their infancy in modern agriculture. We will see much more of them in the future.

FUTURE DILEMMAS

The costs of further gains in yield are becoming greater with each passing year. The costs of capital and energy for crop production are increased by every ton of topsoil that is washed or blown away, by each reservoir filled with silt, and every hectare claimed by desert sand. The cost-multipliers of crop production–social organization and technological sophistication–will also continue to increase as the natural productivity of our crop ecosystems is impaired.

Human-caused stresses on ecosystems, whether they are on hillsides in Venezuela or Pakistan, or on the rangelands of Botswana or Argentina, reduce the ability of the ecosystems to resist "normal" climatic extremes. With mistreatment of ecosystems, troublesome periods of low rainfall become periods of famine, and serious floods became disasters. In 1 month, a layer of fertile topsoil that took hundreds of years to accumulate can be lost because of human mismanagement.

In the United States, the productivity of the Dust Bowl was restored because tremendous technical and financial resources were available. We were also able to purchase food abroad during the lag period while productivity was being rebuilt, thus avoiding prolonged shortages and hardships. But most countries whose agricultural ecosystems are threatened lack the necessary technical skills of agronomy, forestry, horticulture, range management and engineering, which must be simultaneously brought to bear on problems that threaten food production. Social and political differences add to the problems. Those who are barely making a living on degenerating land cannot be expected to plant trees, leave land fallow, and sacrifice livestock if they are not provided with alternative food sources. In the words of a newly elected president of one African country, "We cannot afford conservation, we are not rich enough." Thus, the problem seems to be ever increasing.

Soil conservation must become a matter of ethics and law for crop producers the world over, just as honest weights and measures and the humane treatment of livestock have become matters of ethical concern and legal prescription. To make conservation a vital factor, it may be necessary to sacrifice large short-term gains for smaller profits that accumulate over a long period. In the end, soil conservation implies acceptance (and perhaps pursuit) of a level of biological productivity that can be sustained indefinitely. Soil conservation often provides immediate benefits in terms of plant performance and must be considered a requisite of sound soil management.

Soil has sometimes been called “our most important heritage.” Without a doubt, it is the backbone of agricultural productivity, and the greatness of nations can be measured in terms of their skill and persistence in producing agricultural products. The developing nations will do well to heed the lessons of history, and see that their agricultural base, which is circumscribed by their climates and soils, is carefully developed and protected.

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