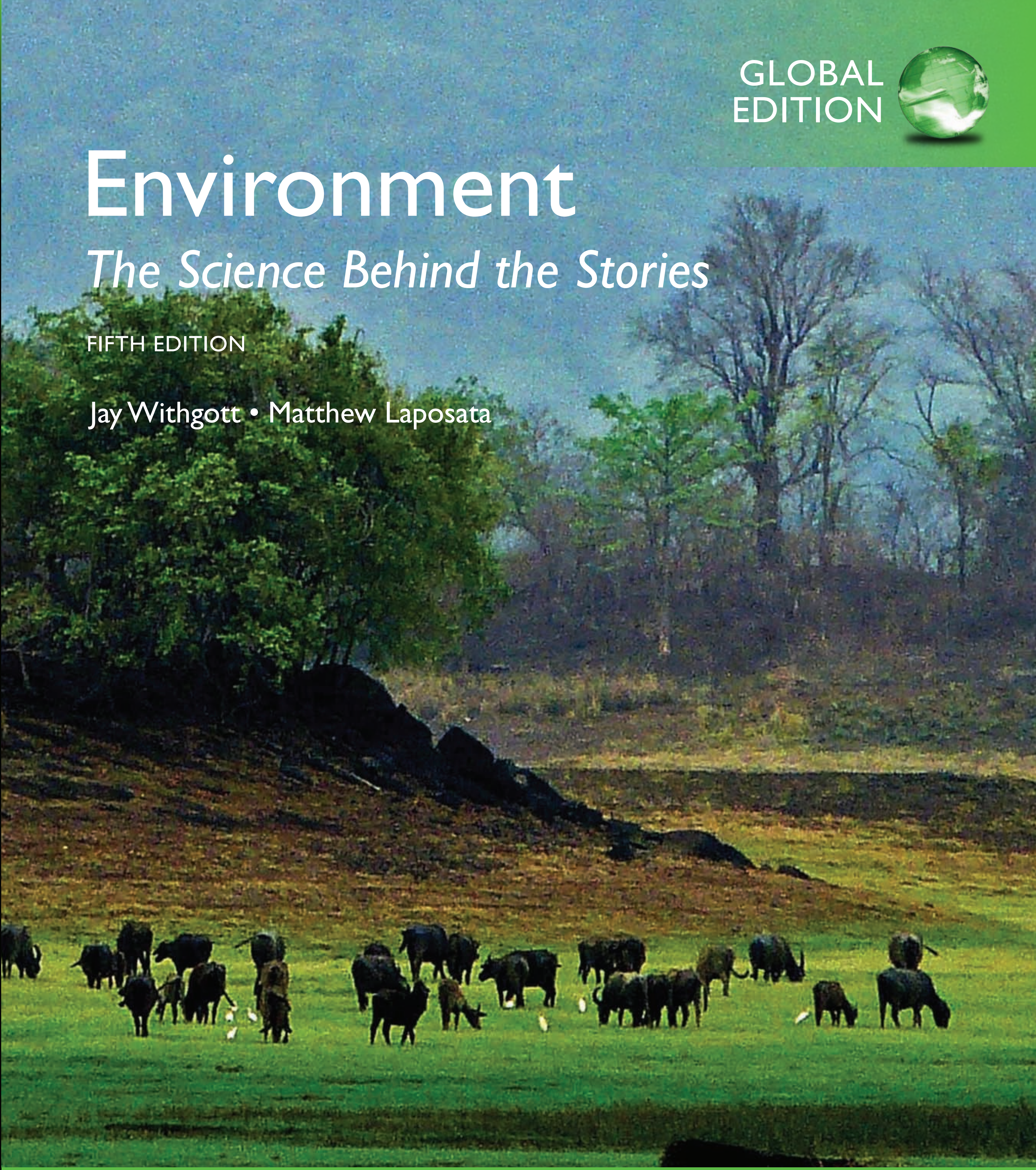
GLOBAL EDITION

Environment

The Science Behind the Stories

FIFTH EDITION

Jay Withgott • Matthew Laposata



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nutrients accessible to their roots. Livestock also depend on soil with these characteristics, because livestock eat plants that have grown in the soil. If soil becomes degraded, then agriculture suffers. Because everyone in our society relies directly on agriculture for the meals we eat and the clothing we wear, the quality of our lives is closely tied to the quality of our soil.

Healthy soil has sustained agriculture for thousands of years. When people first began farming, they were able to take advantage of deep, nutrient-rich topsoil that had built up over vast spans of time. Today we face the challenge of producing immense amounts of food from soil that has been farmed many times, while also conserving its fertility for the future. Before we examine soil closely, let's step back and consider how agriculture came about in the first place and how we got to where we are today.

Agriculture arose 10,000 years ago

During most of the human species' 200,000-year existence, we were hunter-gatherers, depending on wild plants and animals for our food and fiber. Then about 10,000 years ago, as the climate warmed and glaciers retreated, people in some cultures began to raise plants from seed and to domesticate animals.

Agriculture most likely began as hunter-gatherers brought wild fruits, grains, and nuts back to their encampments. Some of these foods fell to the ground, were thrown away, or survived passage through the digestive system. The plants that grew from these seeds likely produced fruits larger and tastier than those in the wild, because they sprang from seeds of fruits that people had selected because they were especially large and delicious. As these plants bred with similar ones nearby, they gave rise to subsequent generations of plants with large and flavorful fruits.

Eventually people realized they could guide this process, and our ancestors began intentionally planting seeds from plants whose produce was most desirable. This practice of selective breeding (p. 70) has produced the many hundreds of crops we enjoy today, all of which are artificially selected versions of wild plants. People followed the same process of selective breeding with animals, creating livestock from wild species.

Evidence from archaeology and paleoecology suggests that agriculture was invented independently by different cultures in at least five areas of the world, and possibly 10 or more (**FIGURE 9.2**). The earliest widely accepted evidence for plant and animal domestication is from the "Fertile Crescent" region of the Middle East at least 10,500 years ago. By studying ancient crop remains, scientists have determined that wheat and barley originated here, as did rye, peas, lentils, onions, garlic, carrots, grapes, and other crops. The people of the Fertile Crescent also domesticated goats and sheep. In China, domestication began 9500 years ago, leading to the rice, millet, and pigs we know today. Agriculture in Africa (coffee, yams, sorghum, and more) and the Americas (corn, beans, squash, potatoes, llamas, and more) developed in several regions 4500–7000 years ago, and likely as much as 10,000 years ago.

Once our ancestors learned to cultivate crops and raise animals, they began to settle in more permanent camps and villages, often near water sources. In a self-reinforcing positive feedback cycle (pp. 124–125), the need to harvest crops kept people sedentary, and once they were sedentary, it made sense to plant more crops. As food supplies became more abundant, carrying capacities (pp. 75–76) increased and populations rose. Population increase, in turn, promoted the intensification of agriculture.

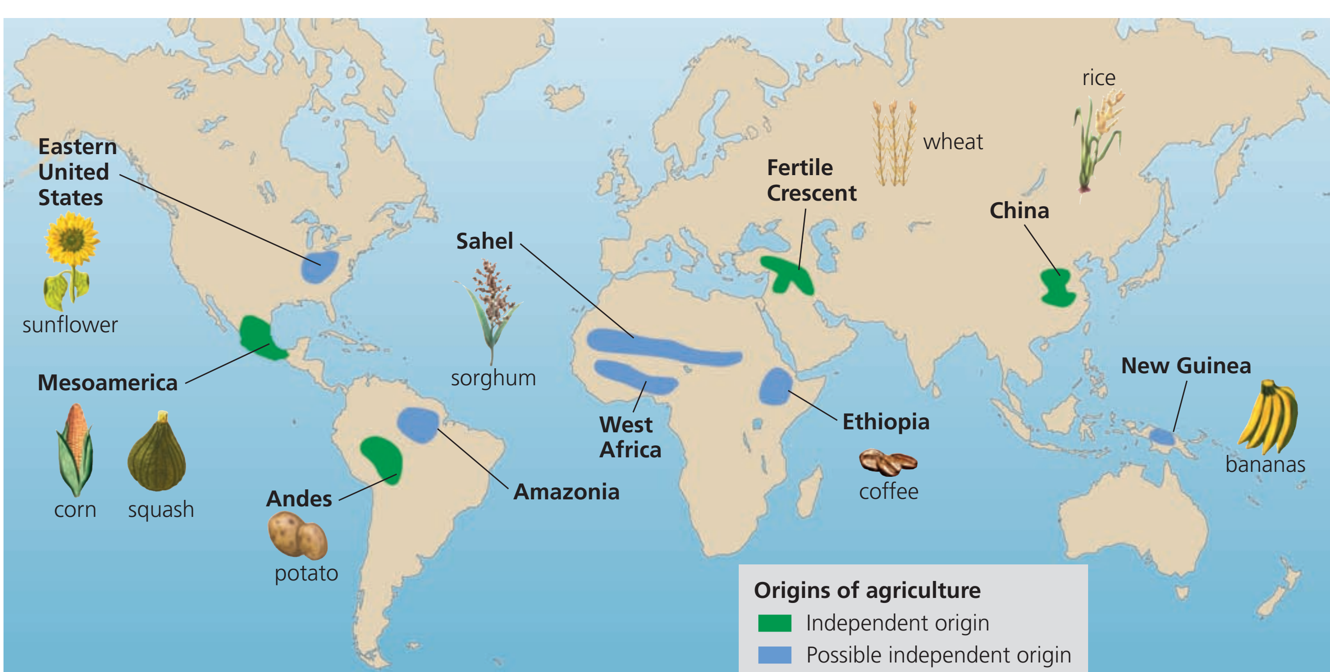


FIGURE 9.2 Agriculture originated independently in multiple regions of the world as different cultures domesticated plants and animals from wild species. *Data from syntheses in Diamond, J., 1997.* Guns, germs, and steel. *New York: W.W. Norton; and Goudie, A., 2000.* The human impact*, 5th ed. Cambridge, MA: MIT Press*.

Moreover, the ability to grow excess farm produce enabled some people to live off the food that others produced. This led to the development of professional specialties, commerce, technology, densely populated urban centers, social stratification, and politically powerful elites. For better or worse, the advent of agriculture eventually brought us the civilization we know today.

Industrial agriculture dominates today

For thousands of years, the work of cultivating, harvesting, storing, and distributing crops was performed by human and animal muscle power, along with hand tools and simple machines—an approach known as **traditional agriculture.** In the oldest form of traditional agriculture, known as **subsistence agriculture,** farming families produce only enough food for themselves. As farmers began integrating into market economies and producing excess food to sell, they started using teams of animals for labor and significant quantities of irrigation water and fertilizer.

The industrial revolution (p. 22) introduced large-scale mechanization and fossil fuel combustion to agriculture, just as it did to industry. Farmers replaced horses and oxen with machinery that provided faster and more powerful means of cultivating, harvesting, transporting, and processing crops. Such **industrial agriculture** also boosted yields by intensifying irrigation and by introducing synthetic fertilizers. In addition, the advent of chemical pesticides reduced competition from weeds and herbivory by crop pests. The use of machinery created a need for highly organized approaches to farming, leading us to plant vast areas with single crops in straight orderly rows. Such **monocultures** ("one type") are distinct from the **polycultures** ("many types") typical of traditional agriculture, such as Native American farming systems that mixed maize, beans, squash, and peppers in the same fields. Today, industrial agriculture occupies over 25% of the world's cropland and dominates areas such as Iowa.

Industrial agriculture spread from developed nations to developing nations with the advent of the **Green Revolution** (see Chapter 10; pp. 265–266). Beginning around 1950, the Green Revolution introduced new technology, crop varieties, and farming practices to the developing world. These advances dramatically increased yields and helped millions avoid starvation. Yet despite its successes, the Green Revolution is exacting a price. The intensive cultivation of monocultures using pesticides, irrigation, and chemical fertilizers has many consequences, and can degrade the integrity of soil, the very foundation of our terrestrial food supply.

Soil as a System

We generally overlook the startling complexity of soil. Although it is derived from rock, soil is molded by living organisms (FIGURE 9.3). By volume, soil consists very roughly of 50% mineral matter and up to 5% organic matter. The rest consists of pore space taken up by air or water. The organic matter in soil includes living and dead microorganisms as well as decaying material derived from plants and animals. A single teaspoon of soil can contain millions of bacteria and thousands of fungi, algae, and protists. Soil provides habitat for earthworms, insects, mites, millipedes, centipedes, nematodes, sow bugs, and other invertebrates, as well as for burrowing mammals, amphibians, and reptiles. The composition of a region's soil strongly influences its ecosystems. In fact, because soil is composed of living and nonliving components that interact in complex ways, soil itself meets the definition of an ecosystem (pp. 78, 128).

Soil forms slowly

The formation of soil plays a key role in terrestrial primary succession (p. 103), which begins when the lithosphere's parent material is exposed to the effects of the atmosphere, hydrosphere, and biosphere (pp. 78, 127). **Parent material** is the base geologic material in a particular location. It may be hardened lava or volcanic ash; rock or sediment deposited by glaciers; wind-blown dunes; sediments deposited by rivers, in lakes, or in the ocean; or **bedrock,** the mass of solid rock that makes up

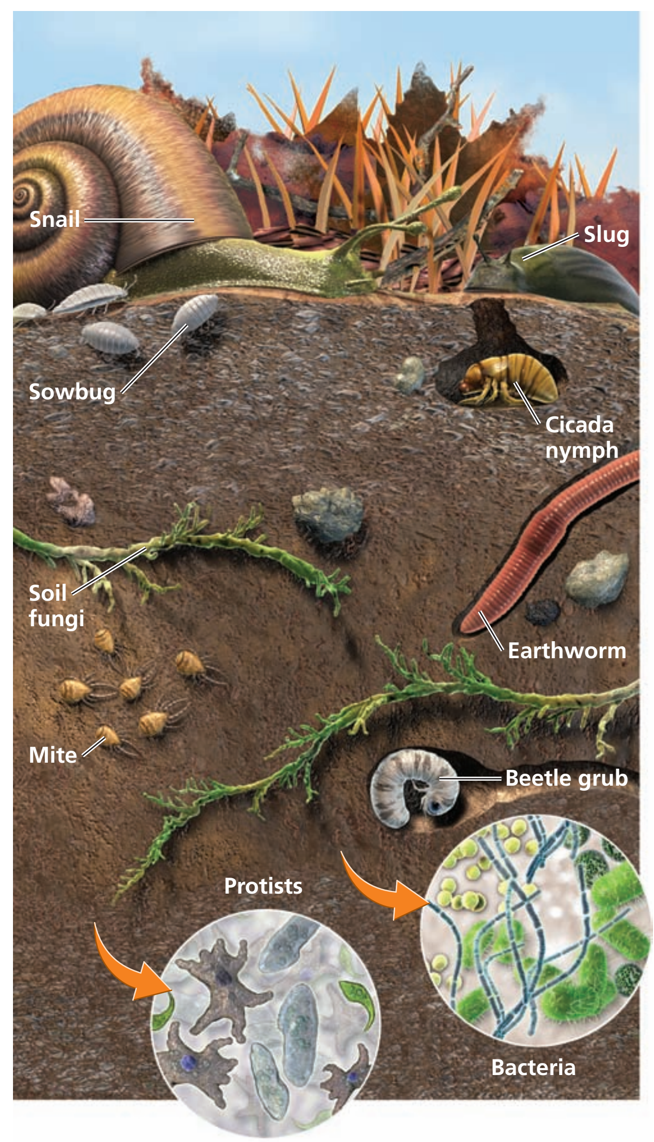


FIGURE 9.3 Soil is a complex mixture of organic and inorganic components and is full of living organisms. In fact, entire ecosystems exist in soil. Most soil organisms decompose organic matter. Some, such as earthworms, also help to aerate the soil.

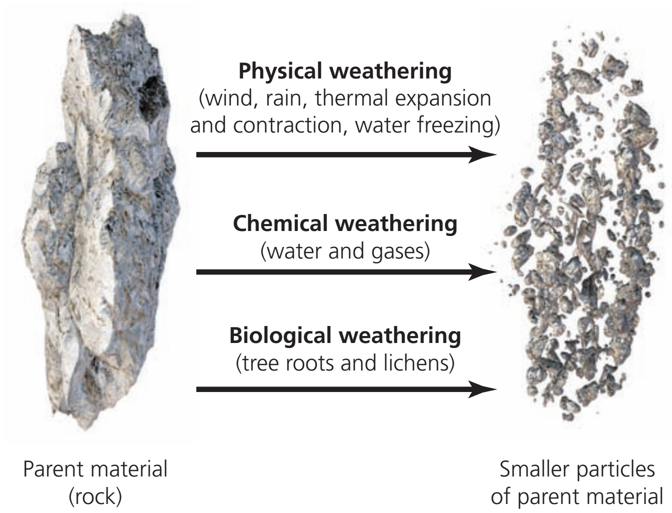


FIGURE 9.4 Weathering breaks down rocks into smaller particles. Physical weathering results from the actions of wind, rain, freezing, and thawing. Chemical weathering occurs as water or gases chemically alter rock. Biological weathering involves living things; for example, lichens (p. 103) produce acid that eats away at rock, and trees' roots rub against rock.

Earth's crust. Parent material is broken down by **weathering,** the physical, chemical, and biological processes that convert large rock particles into smaller particles (**FIGURE 9.4**).

Once weathering has produced fine particles, biological activity contributes to soil formation through the deposition, decomposition, and accumulation of organic matter. As plants, animals, and microbes die or deposit waste, this material is incorporated amid the weathered rock particles, mixing with minerals. For example, the deciduous trees of temperate forests drop their leaves each fall, and detritivores and decomposers (p. 99) break down this leaf litter and incorporate its nutrients into the soil. In decomposition, complex organic molecules are broken down into simpler ones that plants can take up through their roots. Partial decomposition of organic matter creates **humus,** a dark, spongy, crumbly mass of material made up of complex organic compounds. Soils with high humus content hold moisture well and are productive for plant life.

Weathering and the accumulation and transformation of organic matter are the key processes of soil formation, but these are influenced by five main factors:

- *Climate:* Soil forms faster in warm, wet climates, because heat and moisture speed most physical, chemical, and biological processes.
- *Organisms:* Plants and decomposers add organic matter to soil.
- *Topography:* Hills and valleys affect exposure to sun, wind, and water, and they influence how soil moves.
- *Parent material:* Its attributes influence properties of the soil.
- *Time:* Soil formation can take decades, centuries, or millennia.

Because forming just 1 inch of soil can easily require hundreds or thousands of years, we would be wise to conserve the soil we have. Soil is a renewable resource, but it forms so slowly that for all practical purposes we cannot regain fertile soil once it has been lost.

A soil profile consists of horizons

As wind, water, and organisms move and sort the fine particles that weathering creates, distinct layers eventually develop. Each layer of soil is known as a **horizon,** and the cross-section as a whole, from surface to bedrock, is known as a **soil profile.**

The simplest way to categorize soil horizons is to recognize A, B, and C horizons corresponding respectively to topsoil, subsoil, and parent material. However, soil scientists often recognize at least three additional horizons (**FIGURE 9.5**). Soils vary by location, and few soil profiles contain all six horizons, but any given soil contains at least some of them.

Generally, the degree of weathering and the concentration of organic matter decrease as one moves downward in a soil profile. Minerals are transported downward as a result of **leaching,** the process whereby solid particles suspended or dissolved in liquid are transported to another location. Soil that undergoes leaching is a bit like coffee grounds in a drip filter. When it rains, water infiltrates the soil, dissolves some of its components, and carries them downward. Minerals commonly

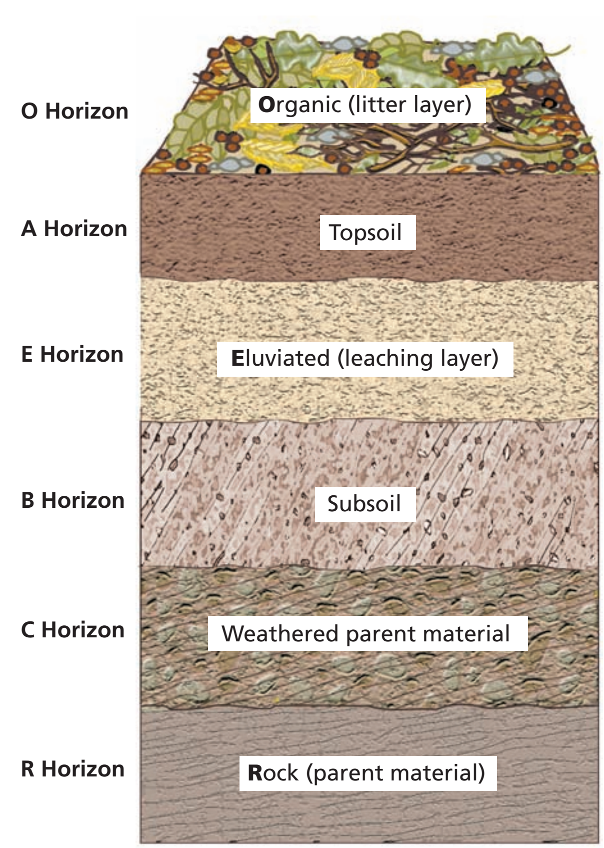


FIGURE 9.5 Mature soil consists of layers, or horizons, that have different compositions and characteristics. Uppermost is the O horizon, or litter layer (O = organic), consisting of organic matter deposited by organisms. Below it lies the A horizon, or topsoil, consisting of some organic material mixed with mineral components. Minerals and organic matter tend to leach out of the E horizon (E = eluviation, or leaching) into the B horizon, or subsoil, where they accumulate. The C horizon of weathered parent material overlies an R horizon (R = rock) of pure parent material.

leached from the E horizon include iron, aluminum, and silicate clay. In some soils, minerals may be leached so rapidly that plants are deprived of nutrients. Minerals that leach from soils may enter groundwater, and some can pose human health risks when the water is extracted for drinking.

A crucial horizon for agriculture and ecosystems is the A horizon, or **topsoil.** Topsoil consists mostly of inorganic mineral components, with organic matter and humus from above mixed in. Topsoil is the portion of the soil that is most nutritive for plants, and it takes its loose texture, dark coloration, and strong water-holding capacity from its humus content. The O and A horizons are home to most of the organisms that give life to soil. Topsoil is vital for agriculture, but agriculture practiced unsustainably over time will deplete organic matter, reducing the soil's fertility and ability to hold water. When a farmer practices no-till farming, he or she essentially creates an O horizon of crop residue to cover the topsoil and then plants seeds of the new crop through this O horizon into the protected topsoil layer.

Soils differ in color, texture, structure, and pH

The six horizons shown in Figure 9.5 depict an idealized soil, but soils display great variety. Scientists classify soils—and farmers judge their quality for farming—based on properties such as color, texture, structure, and pH.

Soil color To a scientist or a farmer, a soil's color can indicate its composition and its fertility. Black or dark brown soils are usually rich in organic matter, whereas a pale color often indicates leaching or low organic content.

Soil texture Soil texture is determined by the size of particles (FIGURE 9.6). **Clay** consists of particles less than 0.002 mm in diameter; **silt,** of particles 0.002–0.05 mm; and **sand,** of particles 0.05–2 mm. Sand grains, as any beachgoer knows, are large enough to see individually and do not adhere to one another. Clay particles, in contrast, readily adhere to one another and give clay a sticky feeling when moist. Silt is intermediate, feeling powdery when dry and smooth when wet. Soil with an even mixture of the three particle sizes is known as **loam.**

Soils with large particles are porous and allow water to pass through quickly—so crops planted in sandy soils require frequent irrigation. Conversely, soils with very fine particles have small pore spaces because particles pack closely together, making it difficult for water and air to pass through. Thus in clay soils water infiltrates slowly and less oxygen is available to soil life. For these reasons, silty soils with medium-sized pores, or loamy soils with a mix of pore sizes, are best for plant growth and agriculture.

Soil structure Soil structure is a measure of the "clumpiness" of soil. An intermediate degree of clumpiness is generally best for plant growth. Repeated tilling can compact soil, reducing its ability to absorb water and inhibiting the penetration of plants' roots.

Soil pH Plants can die in soils that are too acidic or too alkaline, so soils of intermediate pH values (p. 46) are best for most plants. Soil pH influences the availability of nutrients for plants' roots. During leaching, for instance, acids from organic matter may remove some nutrients from the sites of exchange between plant roots and soil particles.

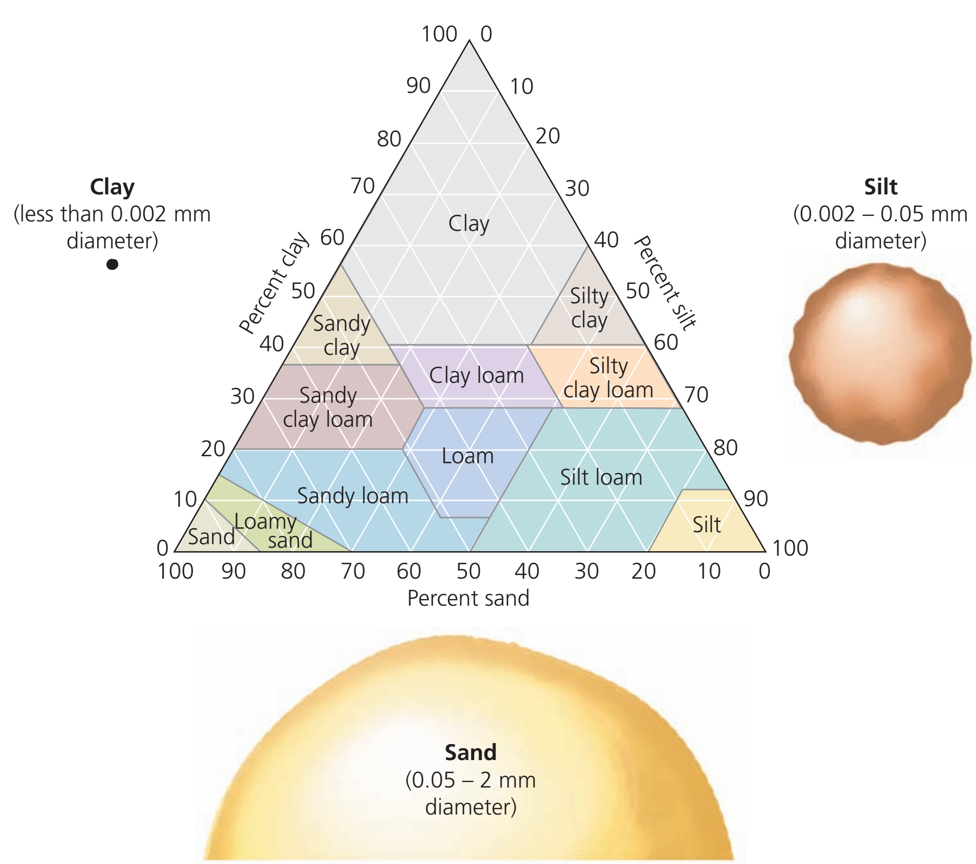


FIGURE 9.6 The texture of soil depends on its mix of particle sizes. Using this diagram, scientists classify soil texture according to the proportions of sand, silt, and clay. After measuring the percentage of each particle size in a soil sample, a scientist can trace the appropriate white lines inward from each side of the triangle to determine texture. Loam is generally best for plant growth, although some plants grow better in other textures.

DATA Q What type of soil contains 20% clay, 60% silt, and 20% sand?

Cation exchange is vital for plant growth

Plants gain many nutrients through a process called **cation exchange.** Soil particle surfaces that are negatively charged hold cations, or positively charged ions (p. 43), such as those of calcium, magnesium, and potassium. In cation exchange, plant roots donate hydrogen ions to the soil in exchange for these nutrient ions, which the soil particles then replenish by exchange with soil water.

Cation exchange capacity expresses a soil's ability to hold cations and prevent them from leaching (thus making them available to plants). This is a useful measure of soil fertility. Soils with fine texture and soils rich in organic matter have high cation exchange capacity. As soil pH becomes lower (more acidic), cation exchange capacity diminishes, nutrients leach away, and soil instead may supply plants with harmful aluminum ions. This is one way in which acid precipitation (pp. 491–493) can damage soils and plant communities.

(a) Tropical swidden agriculture on nutrient-poor soil

(b) Industrial agriculture on Iowa's rich topsoil

FIGURE 9.7 Regional soil differences affect how people farm. In tropical forested areas such as Indonesia **(a)**, farmers pursue swidden agriculture by the slash-and-burn method because tropical rainforest soils **(inset)** are nutrient-poor and easily depleted. On the Iowa prairie **(b)**, less rainfall means fewer nutrients are leached from the topsoil, while organic matter accumulates, forming a thick, dark topsoil layer **(inset)**.

Regional soil differences affect agriculture

Soil characteristics vary from place to place. For example, it may surprise you to learn that the soil of the Amazon rainforest is much less productive than the soil in Iowa. This is because the enormous amount of rain that falls in the Amazon readily leaches minerals and nutrients out of the topsoil and E horizon and down to the water table, below the reach of plants' roots. At the same time, warm temperatures speed the decomposition of leaf litter and the uptake of nutrients by plants, so the thin topsoil layer contains very little humus.

As a result, when tropical rainforest is cleared for farming, cultivation quickly depletes the soil's fertility. This is why the traditional form of agriculture in tropical forested areas is *swidden* agriculture, in which the farmer cultivates a plot for one to a few years and then moves on to clear another plot, leaving the first to grow back to forest (**FIGURE 9.7a**). At low population densities this can be sustainable, but with today's dense human populations, soils may not be allowed enough time to regenerate. As a result, agriculture has degraded the soils of many tropical areas.

On the Iowa prairie, in contrast (**FIGURE 9.7b**), there is less rainfall and less leaching, so nutrients remain within reach of plants' roots. Plants return nutrients to the topsoil as they die, maintaining its fertility. The thick, rich topsoil of temperate grasslands can be farmed repeatedly with minimal loss of fertility if techniques such as no-till farming are used.

FAQ **What is "Slash-and-Burn" Agriculture?**

Soils of tropical rainforests are not well suited for cultivating crops because they contain relatively low levels of plant nutrients. Instead, most nutrients are tied up in the forest's lush vegetation. When farmers cut tropical rainforest for agriculture, they enrich the soil by burning the plants on site. The nutrient-rich ash is tilled into the soil, providing sufficient fertility to grow crops. This practice is called slash-and-burn agriculture. Alas, the nutrients from the ash are usually depleted in one to a few years. At this point, farmers move deeper into the forest and repeat the process, causing further impacts to these productive and biologically diverse ecosystems.

Conserving Soil

If we are to feed the world's rising human population, we will need to modify our diets or increase agricultural production—and do so sustainably, without degrading our soil and its ability to support agriculture. We cannot simply keep expanding farming and grazing into new areas, because land suitable and available for agriculture is running out. Farming or grazing on unsuitable lands can turn grasslands into deserts; remove ecologically precious forests; diminish biodiversity; encourage invasive species; pollute soil, air, and water with toxic chemicals; and allow fertile soil to be blown and washed away. Instead, we must find ways to improve the efficiency of food production in areas already under cultivation, while pursuing agricultural methods that exert less impact on natural systems.

Damage to soil and land makes conservation vital

Each year, our planet gains 80 million people yet loses 5–7 million ha (12–17 million acres, about the size of West Virginia) of productive cropland. Throughout the world, especially in drier regions, it has become more difficult to raise crops and graze livestock as soils deteriorate in quality and decline in productivity—a process termed **soil degradation** (**FIGURE 9.8a**). Soil degradation results primarily from forest removal, cropland agriculture, and overgrazing of livestock (**FIGURE 9.8b**).

Over the past 50 years, scientists estimate that soil degradation has reduced potential rates of food production by 13% on cropland and 4% on rangeland. By mid-century, there will likely be 2 billion more mouths to feed. For these reasons, it is imperative that we learn to practice agriculture in sustainable ways that maintain the integrity of our soil.

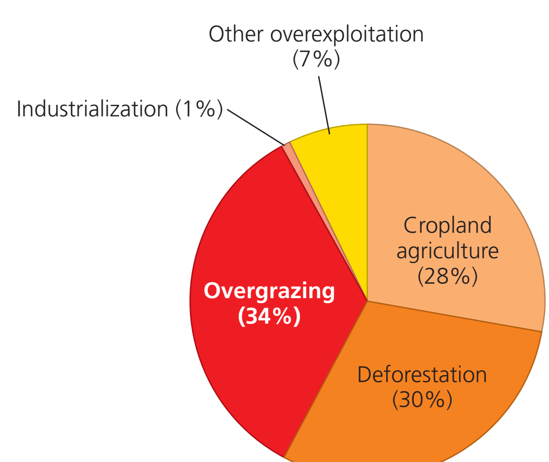
Soil degradation is central to the broader problem known as land degradation. **Land degradation** refers to a general deterioration of land that diminishes its productivity and biodiversity, impairs the functioning of its ecosystems, and reduces the ecosystem services it offers us. Land degradation is caused by the cumulative impacts of unsustainable agriculture, deforestation, and urban development. It is a global phenomenon that affects up to one-third of the world's people. Land degradation is manifested in processes such as soil erosion, nutrient depletion, water scarcity, salinization (p. 252), waterlogging (p. 252), chemical pollution, changes in soil structure and pH, and loss of organic matter from the soil. Scientists, policymakers, farmers, and ranchers are working hard to discover and implement solutions for all of these problems.

Erosion threatens ecosystems and agriculture

Erosion is the removal of material from one place and its transport toward another by the action of wind or water (**FIGURE 9.9**). **Deposition** occurs when eroded material is deposited at a new location. Erosion and deposition are natural processes, and in the long run deposition helps to create soil. Flowing water may deposit freshly eroded sediment rich in nutrients across river valleys and deltas, producing rich and productive soils. This is why floodplains are excellent for farming.

However, erosion is a problem for ecosystems and agriculture because it tends to occur much more quickly than soil

(a) Farmer with degraded soil



(b) Causes of soil degradation

FIGURE 9.8 We have degraded many soils. A farmer **(a)** shows degraded soil in southern China. Most of the world's soil degradation **(b)** results from cropland agriculture, overgrazing by livestock, and deforestation. *Data (b) from Wali, M.K., et al., 1999. Assessing terrestrial ecosystem sustainability: Usefulness of regional carbon and nitrogen models.* Nature and Resources *35: 21–33.*