central
CASE STUDY

Farm to Table (and Back Again) at Kennesaw State University

There are two spiritual dangers in not owning a farm. One is the danger of supposing that breakfast comes from the grocery, and the other that heat comes from the furnace.

Conservationist and philosopher Aldo Leopold

The nation that destroys its soil destroys itself.

U.S. President Franklin D. Roosevelt

It's not surprising to see phrases such as "think globally, eat locally" and "farm to table" when you're dining at a trendy restaurant, but would you expect to see them used at your campus dining hall?

Believe it or not, campus dining services around the country are now among the industry leaders in culinary sustainability, a pursuit that embraces the use of fresh, healthy, locally produced foods to provide diners delicious, nutritious meals. One leader in sustainable dining is Kennesaw State University (KSU) in suburban Atlanta, Georgia. In 2009, the university opened The Commons, a dining facility that serves more than 5000 students each day and was granted gold-level certification as a sustainable building by the Leadership in Energy and Environmental Design (LEED) program (p. 343). The next year, KSU launched a Farm-to-Campus program when it acquired a plot of farmland just off campus.

Today, the university runs three farms on 27 hectares (67 acres) of land near the campus that grow thousands of pounds of produce each year, supplying many of the fruits and vegetables served to students in The Commons. But KSU does even more, and is working to create a fully closed loop system. Uneaten food waste from The Commons is fed into an aerobic digestion system behind the facility, where it is broken down to generate a nutrient-rich liquid. This liquid compost is trucked back to the campus farms and applied there as a fertilizer to nourish the soil and help grow new crops. As KSU's first director of Culinary and Hospitality Services put it, "We go beyond farm-to-campus. We embrace farm-to-campus and back-to-farm operations."

Kennesaw State's ambitious program to mesh sustainable agriculture with campus dining got its start when the university committed to make sustainability a prime consideration in construction and operation of The Commons. KSU's architects and engineers designed a facility that minimizes energy use, water consumption, and waste generation. Illuminated with floor-to-ceiling windows and high-efficiency lighting, The Commons offers nine themed food stations and a rotating menu of 200–300 items. Foods are prepared to order or in small batches according to demand, drastically reducing the amount of leftover food. A "trayless" approach to food service further reduces food waste and the amount of water used in dishwashing.

Tending to crops on a college farm ▲

Upon completing this chapter, you will be able to:

- Outline broad developments in the history of agriculture
- Explain the importance of soils to agriculture
- Discuss the fundamentals of soil science, including soil formation and soil properties
- Describe how farmers supply water to crops, and explain why sustainable alternatives are important
- Describe how farmers supply nutrients to crops, and assess sustainable alternatives
- Explain the importance of pollinators for crop success
- Analyze the causes and impacts of soil erosion and land degradation, and discuss solutions
- Summarize major policy approaches for conservation in agriculture

Kennesaw State University's Hickory Grove Farm as diners without trays tend to eat less and use fewer plates. The Commons has special dishwashing systems designed for water and energy efficiency, napkin dispensers that reduce paper waste, hydration stations for refilling reusable water bottles, and a recycling and composting program that diverts 44,000 pounds of waste from the landfill each month. The facility even generates biodiesel from its used cooking oil (p. 567) to fuel university vehicles.

With an award-winning green building as the anchor of its program, KSU set about creating an agricultural system that could supply diners with fresh, healthy, local produce. The three campus farms grow dozens of items—everything from tomatoes to cucumbers to melons to apples—using practices that protect soil quality by minimizing the use of chemical pesticides and synthetic fertilizers. Indeed, soil quality is enhanced by the application of nutrient-rich compost and liquid from the digester. Sixty free-range chickens produce 300 organic eggs per week, and apiaries house 48 honeybee colonies that produce 30 gallons of honey each year.

On campus, herbs, lettuce, and shiitake mushrooms are grown in an herb garden and greenhouse behind The Commons and in 10 hydroponic stations scattered throughout the dining area. These are each watered with rainwater collected in barrels on the roof of The Commons. There is even a grist mill on site that grinds fresh grits and cornmeal. In addition, the university has cultivated relationships with local farms and meat producers, sourcing locally produced food whenever possible.

KSU's culinary program is receiving wide recognition, and in 2013 Kennesaw State became the first educational institution to win the National Restaurant Association's Innovator of the Year award, beating out competitors such as Walt Disney Parks and Resorts and the U.S. Air Force. That year, the university opened its Institute for Culinary Sustainability and Hospitality, the first such degree program in the United States. Its students learn the culinary, business, and scientific skills required to implement sustainable food practices in restaurants, hotels, hospitals, and schools.

Today at KSU, the links between farm and campus continue to grow. A farmers' market has been established on campus; and a student group, Students for Environmental Sustainability, has launched a permaculture project next to the science building. Student volunteers and interns work at the farms, and new classes in organic farming and beekeeping are using the farms as well.

Kennesaw State has enjoyed unusual success in linking campus and farm to enhance students' dining experiences, but food service operations on many campuses across North America today are embracing fresh locally farmed food as they pursue culinary sustainability in various ways. Michigan State University engages students in organic farming through teaching, research, and production. At California State University, Chico, more than 35 students are employed at the school's 800-acre farm, supplying fruits, vegetables, meat, and dairy products to the dining halls, farmers' markets, and local restaurants. Many dozens of schools—from Hampshire College to Clemson University to Dickinson College to Case Western Reserve University—provide their communities with food through community-supported agriculture (CSA) programs (p. 262).

Altogether, about 70% of America's largest colleges and universities now have a campus farm or garden from which their dining halls can source food directly, according to a recent survey of more than 300 major institutions. Meanwhile, more and more campus dining halls are gaining LEED certification as green buildings. Collectively, these efforts are reducing the ecological footprints of American colleges and universities and pointing the way to a more sustainable food future—all while supplying students with healthy and delicious meals.

The Changing Face of Agriculture

Most of us don't think about agriculture from day to day; after all, most people today live in cities and suburbs, not on farms or ranches. Yet agriculture provides our most basic daily needs, from the food we eat to the clothes we wear. When we eat food from a college dining hall, a grocery store, or a restaurant, that food originated with the efforts of farmers or ranchers working the land to produce crops or raise animals. When we buy shirts, pants, socks, or linens, many of these originated with cotton crops grown and tended by farmers. Our lives depend directly on agriculture—and agriculture is responsible for some of our biggest impacts on the environment, as well. For these reasons, it's important to recognize where our food and fiber come from, to understand how they are produced, and to devise ways of reducing their environmental impacts and making their production sustainable.

Several factors underpin agriculture

We can define **agriculture** as the practice of raising crops and livestock for human use and consumption. We obtain most of our food and fiber from **cropland,** land used to raise plants for human use, and from **rangeland,** or pasture, land used for grazing livestock.

Growing crops and raising animals require inputs of resources. Crops require soil, sunlight, water, nutrients, and mechanisms for pollination. Livestock require food and water. These resources are the factors that underpin agriculture—and making agriculture sustainable means safeguarding their availability and quality. As the human population has grown, so have the amounts of these resources we devote to agriculture. Today we commandeer more than 1 out of every 3 acres of land on Earth to produce food and fiber for ourselves. Rangeland covers 26% of Earth's land surface, and cropland covers 12%. The percentages are even greater in the United States, where nearly half the land is devoted to agriculture. Here, rangeland covers 27% and cropland covers 19% of our land area.

Agriculture led to modern societies

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 in the first place 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 evolutionary process, and our ancestors began intentionally planting seeds from plants whose produce was most desirable. This practice of selective breeding (p. 51) has generated 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 suggests that agriculture was invented independently by different cultures in at least 5 areas of the world, and possibly in 10 or more (**FIGURE 9.1**). The earliest widely accepted evidence for plant and animal domestication comes from the "Fertile Crescent" region of the Middle East at least 10,500 years ago. Wheat and barley originated in this region, as did rye, peas, lentils, onions, garlic, carrots, grapes, and domesticated goats and sheep. In China, domestication began 9500 years ago, leading to the varieties of 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 at least 4500–7000 years ago, and likely as much as 10,000 years ago.

In one mainstream scholarly view, 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 cycle of positive feedback (p. 104), 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 (p. 65) increased and populations rose. Population increase, in turn, promoted the intensification of agriculture.

Moreover, the ability to grow excess farm produce enabled some people to live off the food that others produced. This eventually 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 may be largely responsible for 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 past, most traditional farmers produced only enough food for their own

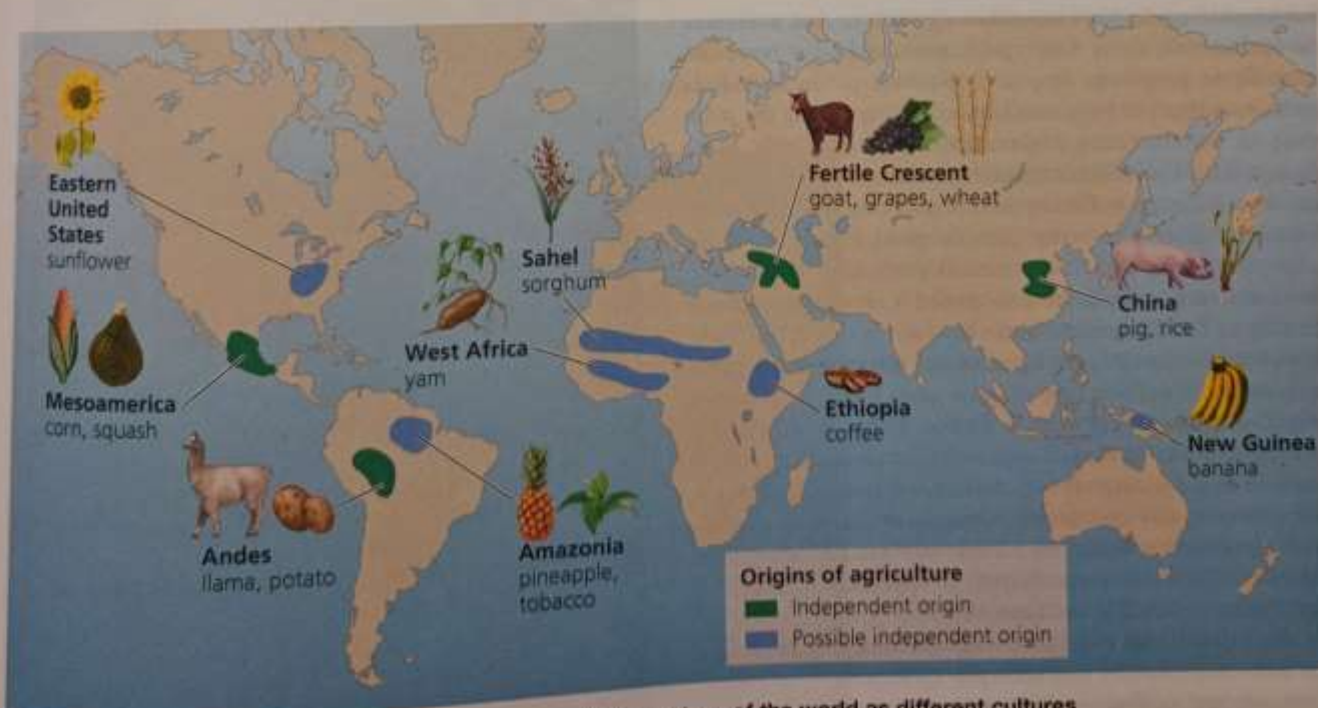


FIGURE 9.1 Agriculture originated independently in multiple regions of the world as different cultures domesticated plants and animals from wild species. *Data from Diamond, J., 1997. Guns, germs, and steel. New York, NY: W.W. Norton; and Goudie, A., 2000. The human impact, 5th ed. Cambridge, MA: MIT Press.*

subsistence. Today many have integrated into market economies and produce excess food to sell, using teams of animals for labor and significant quantities of irrigation water and fertilizer.

The industrial revolution (p. 5) introduced large-scale mechanization and fossil fuel combustion to agriculture, just as it did to industry. Many farmers in industrializing societies 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 introducing synthetic fertilizers, while the advent of chemical pesticides reduced herbivory by crop pests and competition from weeds. The use of machinery created a need for highly organized approaches to farming, leading large-scale farmers 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.

Industrial agriculture spread from developed nations to developing nations with the advent of the Green Revolution (see Chapter 10; p. 238). 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, industrial agriculture is exacting a price. The intensive cultivation of monocultures using pesticides, irrigation, and chemical fertilizers has many consequences, among them the degradation of soil, water, and pollinators that we rely on for our terrestrial food supply.

Sustainable agriculture reduces environmental impacts

Sustainable agriculture describes agriculture that maintains the healthy soil, clean water, pollinators, and other resources essential to long-term crop and livestock production. It is agriculture that can be practiced in the same way in the same place far into the future while maintaining high yields. Making agriculture sustainable involves reducing fossil fuel inputs and decreasing the pollution these inputs cause. The farms at Kennesaw State University provide good examples; there, crops are grown with few chemical pesticides or synthetic fertilizers, and harvests are transported a very short distance directly to The Commons, where the food is consumed. Subsequently, food waste is composted and returned to the farms to nourish the soil and help to grow more food. This circular recycling-oriented approach is another hallmark of sustainable agriculture. In overall approach, sustainable agriculture seeks to treat agricultural systems as ecosystems. To this end, many farmers and agricultural scientists are creating agricultural systems that better mimic the way natural ecosystems function. (We will explore a variety of approaches for making agriculture sustainable in Chapter 10.)

In the sections that follow, we will examine several of the most basic factors that underpin agriculture—soil, water, nutrients, and pollinators. We will study the threats to these vital resources, and we will see how farmers, ranchers, scientists, and policymakers are working to conserve them.

Soil: A Foundation of Agriculture

Soil supports all of Earth's terrestrial ecosystems, and healthy soil is vital for agriculture. When we abuse soil, we hamper its ability to sustain our production of food and fiber. Because every one of us 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.

Soil is a living system

Soil is a multifaceted system consisting of disintegrated rock, organic matter, water, gases, nutrients, and microorganisms. Although it is derived from rock, soil is shaped by living organisms (**FIGURE 9.2**). By volume, soil consists roughly of

FIGURE 9.2 Soil, a complex mixture of organic and inorganic components, is full of living organisms. Most soil organisms decompose organic matter. Some, such as earthworms, also help to aerate the soil.

50% mineral matter and up to 5% organic matter. The rest consists of the space between soil particles (pore space) taken up by air or water. The organic matter in soil includes living and dead microorganisms as well as decaying material from plants and animals. The composition of a region's soil strongly influences the character of 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. 59, 110).

Soil supports agriculture

Agriculture relies on healthy soil in several ways (FIGURE 9.3). Crop plants depend on soil that contains organic matter to provide the nutrients they need for growth. Plants also need soil with a structure and texture suitable for roots to penetrate deeply, which assists with uptake of water and nutrients, allowing for proper growth. Plants need soil that holds water and dissolved nutrients in a way that makes them accessible to plant roots. And plants also depend on living organisms in the soil. In particular, many fungi form symbiotic mutualistic associations with plant roots, called *mycorrhizae* (p. 78). The dense network of fungal tissue in the soil helps draw up water and minerals, some of which are passed to the plant, and the plant provides to the fungus the carbohydrates produced by photosynthesis. Wheat and many other crops rely on mycorrhizae for proper growth. Animal agriculture also depends on soil with all these characteristics; because animals subsist on plants, the livestock we raise rely indirectly on healthy 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 soils 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.

Productive soil is a renewable natural resource; once depleted, soil may renew itself over time. However, renewal generally occurs very slowly. Most farming and grazing practiced so far has depleted soils faster than they form, so it is imperative for our civilization's future that we develop sustainable methods of working with soil.

FAQ

Isn't soil just lifeless dirt?

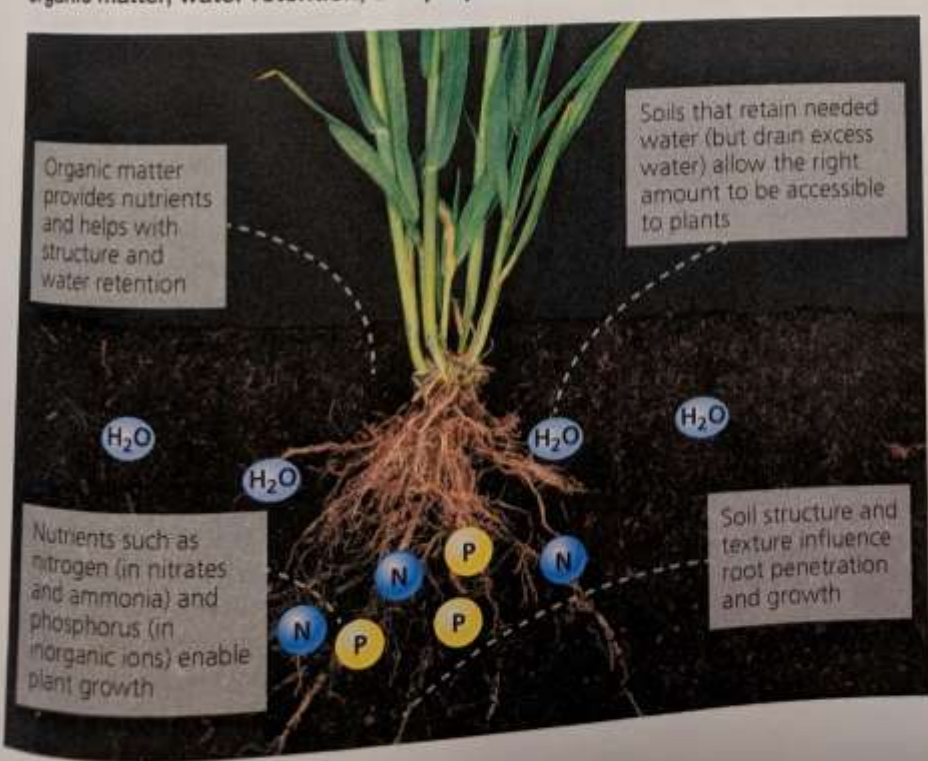
Don't let appearances fool you—healthy soil is a complex ecological system full of life! A single teaspoon of soil can contain millions of bacteria and thousands of fungi, algae, and protists. Soil provides habitat for earthworms, insects, mites, millipedes, centipedes, nematodes, sow bugs, and other invertebrates, as well as for burrowing mammals, amphibians, and reptiles. These organisms improve the nutrient content of soil as well as its texture for retaining water and helping plants' roots to grow. In general, where we find soil rich in life, we find thriving ecological communities aboveground and excellent conditions for agriculture.

Soil forms slowly

The formation of soil plays a key role in terrestrial primary succession (p. 83), which begins when the lithosphere's parent material is exposed to the effects of the atmosphere, hydrosphere, and biosphere. **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 Earth's crust. Parent material is broken down by **weathering,** the physical, chemical, and biological processes that convert large rock particles into smaller particles. Physical weathering results from wind, rain, freezing, and thawing. Chemical weathering occurs as water or gases chemically alter rock. Biological weathering involves living things; for example, lichens (p. 83) produce acid that eats away at rock, and trees' roots rub against rock.

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, making leaf litter available to the detritivores and decomposers (p. 78) that break it down 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.

FIGURE 9.3 Crop plants such as wheat depend on healthy soil for nutrients, organic matter, water retention, and proper root growth.



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. For example, soils on the Kennesaw State University farms have an abundance of well-developed humus because they are regularly resupplied with organic material collected from dining hall operations.

Weathering and the accumulation and transformation of organic matter 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.

Although soil is a renewable resource, it forms so slowly that for all practical purposes we cannot regain soil once it has been lost. 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.

A soil profile consists of horizons

As wind, water, and organisms move and sort the fine particles that weathering creates, distinct layers of soil eventually develop. Each layer is known as a **soil 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 9.4**). 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 minerals 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 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 are leached from soils may enter groundwater, and some can pose human health risks when the affected 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 topsoil's fertility and ability to hold water.

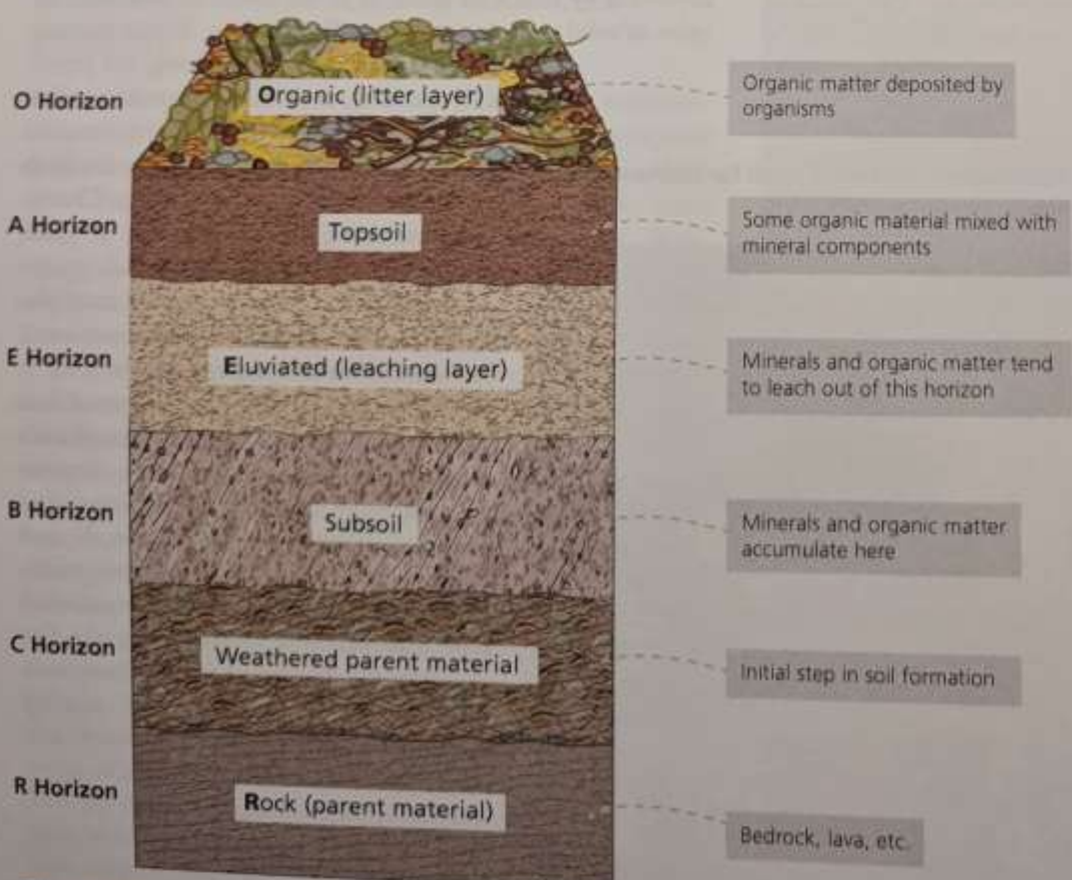


FIGURE 9.4 Mature soil consists of layers, or horizons, that have different attributes.

Soils differ in quality

The six horizons shown in Figure 9.4 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.

Color 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 a history of leaching or low organic content.

Texture Soil texture is determined by the size of particles (FIGURE 9.5). **Clay** particles are less than 0.002 mm in diameter; **silt**, 0.002–0.05 mm; and **sand**, 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—so in clay soils, water infiltrates slowly and less oxygen is available to soil life. For these reasons, the best soils for plant growth and agriculture tend to be silty soils with medium-sized pores, or loamy soils with a mix of pore sizes.

Structure Soil structure is a measure of the "clumpiness" of soil. An intermediate degree of clumpiness is generally best for plant growth. Soil can be compacted by excessive foot traffic or by repeated plowing; this compaction reduces the soil's ability to absorb water and inhibits the penetration of plants' roots.

pH Plants can die in soils that are too acidic or too alkaline, so soils of intermediate pH values (p. 27) are best for most plants. Soil pH influences the availability of nutrients for plants' roots. For instance, acids from organic matter may leach some nutrients from the sites of exchange between plant roots and soil particles.

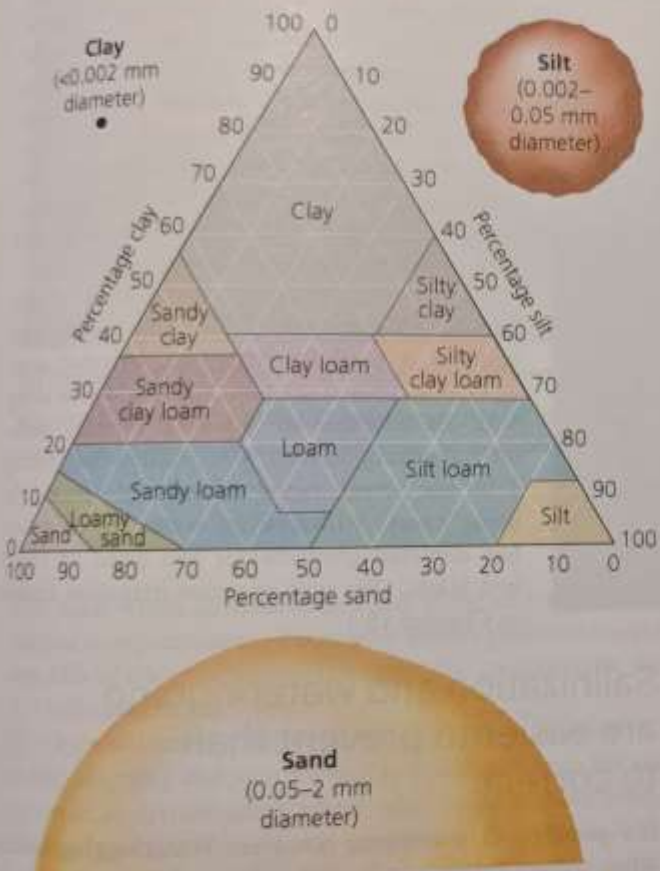


FIGURE 9.5 The texture of soil depends on its mix of particle sizes. Using this diagram, scientists classify soil texture according to the proportions of sand, silt, and clay. After measuring the percentage of each particle size in a soil sample, a scientist can trace the appropriate white lines inward 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?

Go to **Interpreting Graphs & Data** on MasteringEnvironmentalScience®.

Regional soil differences affect agriculture

Soil characteristics vary from place to place, and they are affected by climate and other variables. For example, it may surprise you to learn that soils of the Amazon rainforest are much less productive than soils in Iowa or Kansas. This is because the enormous amount of rain that falls in tropical regions such as the Amazon basin readily leaches minerals and nutrients out of the topsoil and E horizon, below the reach of plants' roots. At the same time, warm temperatures in the Amazon speed the decomposition of leaf litter and the uptake of nutrients by plants, so only small amounts of humus remain in the thin topsoil layer.

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. Plots are often burned before planting, in which case the practice is called **slash-and-burn** agriculture (FIGURE 9.6a, p. 216). At low population densities this process can be sustainable, but with today's dense human populations, soils are often not allowed enough time to regenerate—and increasingly, farmed plots are converted to pasture for ranching.

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. Unfortunately, the nutrients from the ash are usually depleted in just a few years. At this point, farmers move deeper into the forest and slash and burn another swath of land, causing additional impacts to these productive and biologically diverse ecosystems.

grasslands, which can be farmed repeatedly with minimal loss of fertility as long as farmers guard against loss of soil.

Water for Agriculture

Just as soil is a crucial resource for farming and ranching, so is water. Plants require water for growth, and we have long provided our crops and our livestock with supplemental water when needed to boost production.

Irrigation boosts productivity

The artificial provision of water beyond that which crops receive from rainfall is known as **irrigation.** Some crops, such as rice and cotton, use large amounts of water and generally require irrigation, whereas others, such as beans and wheat, need relatively little water. The amount of water a crop requires also is influenced by the rate of evaporation and by the soil's ability to hold water and make it available to plant roots. If the climate is dry, or if too much water evaporates or runs off before it can infiltrate the soil, crops may require irrigation. By irrigating crops, people can farm in arid regions (FIGURE 9.7) and may maintain high yields in times of drought.

Fully 70% of all fresh water that people withdraw from rivers, lakes, and underground aquifers is used for irrigation. Irrigated acreage has increased dramatically worldwide along with the adoption of industrial farming methods, reaching almost 400 million ha (nearly 1 billion acres), twice the area of Mexico. In some cases, withdrawing water for irrigation has depleted groundwater and dried up rivers and lakes. (We will examine irrigation further in Chapter 15.)

(a) Slash-and-burn agriculture on nutrient-poor soil in the tropics

(b) Industrial agriculture on rich topsoil in Iowa

FIGURE 9.6 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, and more organic matter accumulates, forming a thick, dark topsoil layer **(inset).**

As a result, agriculture has degraded the soils of many tropical areas.

In contrast, on the grasslands of North America, which have been almost entirely converted to agriculture (FIGURE 9.6b), there is less rainfall and therefore less leaching, so nutrients remain within reach of plants' roots. Plants return nutrients to the topsoil as they die, maintaining its fertility. This creates the thick, rich topsoil of temperate

Salinization and waterlogging are easier to prevent than to correct

It's possible to overwater, however. **Waterlogging** occurs when overirrigation saturates the soil and causes the water table to rise to the point that water drowns plant roots, depriving them of access to gases and essentially suffocating them.

A more frequent problem is **salinization,** the buildup of salts in surface soil layers. In dryland areas where precipitation and humidity are low, the evaporation of water from the soil's A horizon may pull water containing dissolved salts up from lower horizons. As the water evaporates at the surface, those salts remain, often turning the soil surface white. Irrigation in arid areas generally hastens salinization, and irrigation water often contains some dissolved salt in the

(a) Flood-and-furrow irrigation of cotton in the southern California desert near the Colorado River

(b) Center-pivot irrigation in the southern California desert

FIGURE 9.7 Irrigating water-thirsty crops in arid regions causes us to lose a great deal of water to evaporation.

first place, which introduces new salt to the soil. Salinization inhibits crop production; it currently lowers yields on roughly one-fifth of all irrigated cropland globally, costing more than $11 billion each year.

Once salinization has occurred, one way to alleviate it is to stop irrigating and wait for rain to flush salts from the soil. However, in dryland areas where salinization is most often a problem, precipitation is rarely adequate to flush soils. A better solution may be to plant salt-tolerant plants, such as barley, that can be used as food or pasture. A third option is to bring in large quantities of less-saline water (if available) to flush the soil. However, using too much water may cause waterlogging.

Because remedying salinization once it has occurred is expensive and difficult, preventing it in the first place is better. The best way to prevent salinization is to avoid planting crops that require a great deal of water in dryland areas. A second way is to irrigate with water low in salt content. A third way is to irrigate efficiently, supplying no more water than a crop requires.

Sustainable approaches to irrigation maximize efficiency

One of the most effective ways to reduce water use in agriculture is to better match crops and climate. Many arid regions have been converted into productive farmland through extensive irrigation, often with the support of government subsidies that make irrigation water artificially inexpensive. Some farmers in these areas cultivate crops that require large amounts of water, such as rice and cotton. This leads to extensive water loss from evaporation in the arid climate. Choosing other crops that require far less water could enable these areas to remain agriculturally productive while greatly reducing water use.

Another approach is to embrace technologies that improve efficiency in water use. Currently, irrigation efficiency worldwide is low, as plants end up using only about 40% of the water that we apply. The rest evaporates or soaks into the soil away from plant roots (**FIGURE 9.8a**). Drip irrigation systems that target water directly toward plant roots

(a) Conventional irrigation

(b) Drip irrigation

FIGURE 9.8 Irrigation methods vary in their water use. Conventional methods **(a)** are inefficient, because most water is lost to evaporation and runoff. In drip irrigation systems **(b)**, hoses drip water directly into soil near plants' roots, so that much less is wasted.

through hoses or tubes can increase efficiencies to more than 90% (FIGURE 9.8b). Such drip irrigation systems are used on the Kennesaw State University campus farms that supply The Commons with much of its produce, greatly reducing water use. In addition, rainwater is gathered in barrels atop the roof of the Commons; rainwater harvesting is another technique for making good use of water. As systems for drip irrigation and rainwater harvesting become more affordable, more farmers, gardeners, and homeowners are turning to them.

Nutrients for Plants

Along with water and soil, nutrients are vital for plant growth, and thus for cropland agriculture. Plants require nitrogen, phosphorus, and potassium to grow, as well as smaller amounts of more than a dozen other nutrients. Plants remove these nutrients from soil as they grow, as does leaching. If farmland soil is depleted of nutrients, crop yields decline. For this reason, farmers enhance nutrient-limited soils by adding **fertilizer,** substances that contain essential nutrients.

(a) Inorganic fertilizer

(b) Organic fertilizer

FIGURE 9.9 Two main types of fertilizer exist. Inorganic fertilizer **(a)** consists of synthetically manufactured granules. Organic fertilizer **(b)** includes substances such as compost crawling with natural decomposers like earthworms.

Fertilizers boost crop yields but can be overapplied

There are two main types of fertilizers (FIGURE 9.9). **Inorganic fertilizers** are mined or synthetically manufactured mineral supplements. **Organic fertilizers** consist of the remains or wastes of organisms and include animal manure; crop residues; charcoal; fresh vegetation; and **compost,** a mixture produced when decomposers break down organic matter such as food and crop waste in a controlled environment.

One of the highlights of the culinary sustainability efforts at Kennesaw State University is its closed-loop system for recycling wastes. Uneaten food and scraps from food preparation are placed in a large aerobic digester tank outside the dining hall. Over time, the food items break down inside the digester, generating roughly 1900 L (500 gal) of nutrient-rich "compost tea" each day. This liquid is trucked to the nearby campus farms, where it is used as an organic fertilizer.

Historically, people relied on organic fertilizers to replenish soil nutrients, but during the latter half of the 20th century many farmers in industrialized nations and nations experiencing the Green Revolution embraced inorganic fertilizers (FIGURE 9.10). Inorganic fertilizers have boosted our global food production, but their overapplication has triggered increasingly severe pollution problems. Because inorganic fertilizers are generally more susceptible to leaching and runoff than are organic fertilizers, they more readily contaminate surface water bodies and groundwater supplies.

Nutrients from inorganic fertilizers can have impacts far beyond the boundaries of the fields on which they are applied (FIGURE 9.11). For instance, nitrogen and phosphorus runoff from farms and other inland sources spurs phytoplankton blooms in the Chesapeake Bay (p. 104), the Gulf of Mexico (p. 406), and other marine and coastal regions, creating oxygen-depleted "dead zones" that kill fish and shellfish.

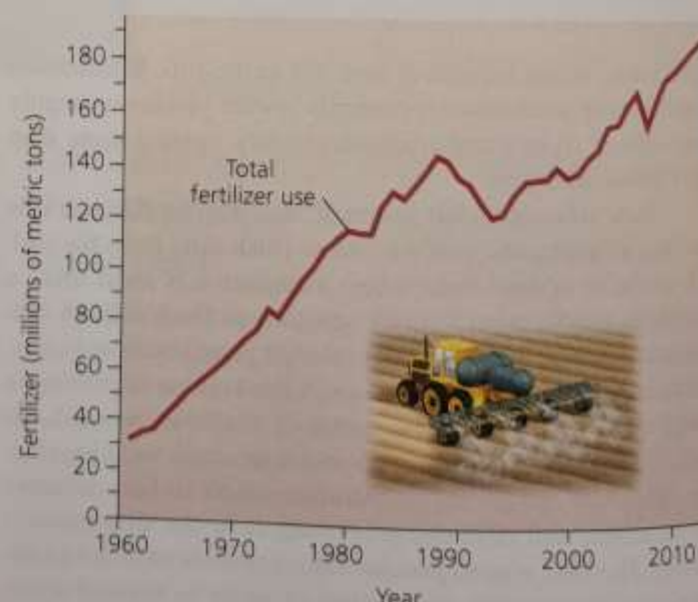


FIGURE 9.10 Use of synthetic, inorganic fertilizers has risen sharply over the past half-century. Today, usage stands at more than 190 million metric tons annually. *Data from International Fertilizer Industry Association and UN Food and Agriculture Organization (FAO).*

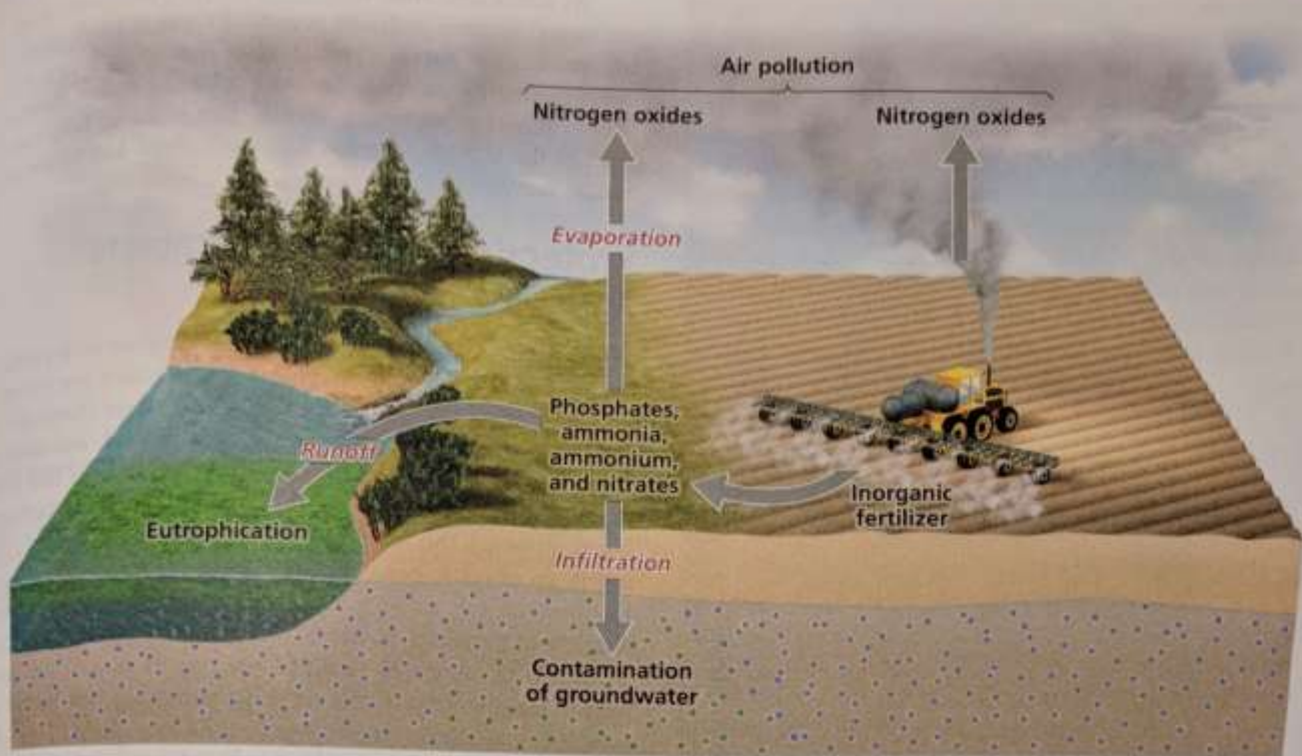


FIGURE 9.11 Overapplication of fertilizers has impacts beyond the farm field, because nutrients not taken up by plants end up elsewhere. Nitrates can leach into aquifers and contaminate drinking water. Runoff of phosphates and nitrogen compounds can alter the ecology of waterways by eutrophication. Compounds such as nitrogen oxides may pollute the air.

Such eutrophication (pp. 109, 406) occurs at countless river mouths, lakes, and ponds throughout the world. Moreover, nitrates are readily leached through soil and contaminate groundwater. Components of some nitrogen fertilizers can even volatilize (evaporate) into the air, contributing to photochemical smog (p. 462) and acid deposition (p. 469). Through these processes, unnatural amounts of nitrates and phosphates spread through ecosystems and can pose human health risks, including cancer and methemoglobinemia, a disorder that can asphyxiate and kill infants. Indeed, human inputs of nitrogen have modified the nitrogen cycle and now account for one-half the total nitrogen flux on Earth (p. 124).

Sustainable fertilizer use involves targeting and monitoring nutrients

Sustainable approaches to fertilizing crops with inorganic fertilizers target the delivery of nutrients to plant roots and avoid the overapplication of fertilizer. Farmers using drip irrigation systems can add fertilizer to irrigation water, thereby releasing it only above plant roots. Growers practicing no-till farming or conservation tillage (p. 226) often inject fertilizer along with seeds, concentrating it near the developing plant. Farmers can also avoid overapplication by regularly monitoring soil nutrient content and applying fertilizer only when nutrient levels are too low. These types of approaches are examples of **precision agriculture,** which involves using technology to precisely monitor crop conditions, crop needs, and resource use, to maximize production while minimizing waste of resources. In addition, by planting buffer strips of vegetation along field edges and watercourses, growers can help to capture nutrient runoff before it enters streams and rivers.

Sustainable agriculture embraces the use of organic fertilizers, because they can provide some benefits that inorganic fertilizers cannot. Organic fertilizers provide not only nutrients but also organic matter that improves soil structure, nutrient retention, and water-retaining capacity. For example, *biochar* is a term for charcoal (wood heated in the absence of oxygen) used as a soil amendment. Biochar was mixed into soil by Amazonian people for centuries to increase soil fertility and crop productivity, and today it is also being considered as a means of carbon sequestration (p. 538).

The use of organic fertilizers is not without cost, though. When manure is applied in amounts needed to supply sufficient nitrogen for a crop, it may introduce excess phosphorus, which can run off into waterways. Accordingly, sustainable approaches do not rely solely on organic fertilizers but integrate them with the targeted use of inorganic fertilizer.

Pollination

Like all plants, crops need to be pollinated to set seed and produce fruit. **Pollination** (p. 78) is the process by which male sex cells of a plant (pollen) fertilize female sex cells of a plant (ova, or egg cells). Pollination can occur in different ways. Plants such as grasses and conifer trees are pollinated thanks to the wind. Millions of minuscule pollen grains are blown long distances, and by chance a small number land on the female parts of other plants of their species. In contrast, the many kinds of plants that sport showy flowers are typically pollinated by animals, such as hummingbirds, bats, and insects (see Figure 4.8, p. 78). Flowers are evolutionary adaptations that function to attract pollinators; the sweet smells and bright colors of flowers are signals that advertise the sugary nectar and protein-rich pollen within. Animals seeking nectar and pollen are drawn to flowers, and they end up transferring pollen from flower to flower as they visit them. This enables flowering plants to reproduce, set seed, and create fruits.

Many crops rely on pollinators

Our staple grain crops, such as wheat and corn, are derived from grasses and are wind-pollinated, but many fruit, vegetable, and nut crops depend on insects for pollination. The insects that pollinate our crops are among the most vital (yet least appreciated) factors contributing to our food production. They provide more than $150 billion of ecosystem services each year, and without them we would have trouble producing enough food to feed our population. Pollinators are the unsung heroes of agriculture.

The most complete survey on pollination to date, undertaken by tropical bee biologist Dave Roubik, documented 800 types of cultivated plants that rely on bees and other insects for pollination. An estimated 73% of these types are pollinated by bees, 19% by flies, 5% by wasps, 5% by beetles, and 4% by moths and butterflies. Bats pollinate 6.5% and birds 4%. Overall, native species of bees in the United States alone are estimated to provide $3 billion of pollination services each year to crop agriculture.

The European honeybee (*Apis mellifera*)—introduced to America from the Old World many decades ago—underpins modern agriculture like no other pollinator. Farmers and orchardists regularly hire beekeepers to bring hives of domesticated honeybees to their fields and orchards when it is time to pollinate crops (**FIGURE 9.12**).

FIGURE 9.12 Beekeepers bring hives of honeybees to farmers' crops when it is time for flowers to be pollinated.

At Kennesaw State University's farms, honeybees from the farms' apiaries pollinate dozens of types of crops, ensuring productive harvests while also producing honey for consumption on campus. Across the United States, honeybees pollinate more than 100 crops that make up fully one-third of the U.S. diet, providing an estimated $15 billion in annual services.

Protecting pollinators protects agriculture

When we harm pollinating insects we harm our crop yields, but by encouraging pollinators we can enhance our yields. As one example of many, the U.S. Great Basin states are a world center for the production of alfalfa seed, and alfalfa flowers are pollinated mostly by native alkali bees that live in the soil as larvae. In the mid-20th century, many farmers began plowing the land and increasing chemical pesticide use in an effort to boost yields. These measures killed vast numbers of the soil-dwelling bees, and alfalfa seed production plummeted in areas where alkali bees were lost. However, farmers who realized the importance of the bees began transplanting divots of soil containing bee larvae to establish and manage new populations near their crops. By encouraging these native bees, these farmers were able to raise yields of alfalfa seed from 300–600 lb/acre to 1000–2400 lb/acre.

Today many pollinating insects are in trouble. Mostly as a result of pesticide use and habitat loss, populations of native pollinators are dwindling and species are disappearing from region after region. At the same time, European honeybees are suffering dramatic declines, and scientists are rushing to learn why and to help us respond (p. 245). (We will examine these losses, assess the risks and impacts, and explore solutions in our discussion of pollinator conservation in Chapter 10.) Finding ways to conserve pollinators is a crucial step to attaining sustainable agriculture.

Conserving Agricultural Resources

Today we face challenges with each of the key resources necessary for agriculture: soil, water, nutrients, and pollinators. If we are to feed the world's rising human population, we will need to modify our diets or increase agricultural production (or both)—and do so sustainably, without degrading our resources. We cannot simply keep expanding farming and grazing into new areas, because land suitable and available for agriculture is running out. When we pursue farming or grazing on unsuitable lands, it 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.