CHAPTER 11

Agriculture, Aquaculture, and the Environment

Modern agriculture uses modern technology (here a computer controls more than 100 center-pivot sprinklers) but continues to depend on the environment in major ways (here the need for water to grow wheat, alfalfa, potatoes, and melons along the Columbia River near Hermiston, Oregon).

LEARNING OBJECTIVES

The big question about farming and the environment is: Can we produce enough food to feed Earth's growing human population, and do this sustainably? The major agricultural challenges facing us today are to increase the productivity of the land, acre by acre, hectare by hectare; to distribute food adequately around the world; to decrease the negative environmental effects of agriculture; and to avoid creating new kinds of environmental problems as agriculture advances. After reading this chapter, you should understand . . .

- How agroecosystems differ from natural ecosystems;
- What role limiting factors play in determining crop yield;
- How the growing human population, the loss of fertile soils, and the lack of water for irrigation can lead to future food shortages worldwide;
- The relative importance of food *distribution* and food *production*;
- Why some lands are best used for grazing, but how overgrazing can damage land;
- How alternative agricultural methods—including integrated pest management, no-till agriculture, mixed cropping, and other methods of soil conservation—can provide major environmental benefits;
- That genetic modification of crops could improve food production and benefit the environment, but perhaps also could create new environmental problems.

CASE STUDY

Biofuels and Banana Chips: Food Crops vs. Fuel Crops

In 2007 Alfred Smith, a farmer in Garland, North Carolina, was feeding his pigs trail mix, banana chips, yogurt-covered raisins, dried papaya, and cashews, according to an article in the *Wall Street Journal*.[1] The pigs were on this diet, Mr. Smith says, because the demand for the biofuel ethanol, produced from corn and other crops, had driven up prices of feed (the largest cost of raising livestock) to the point where it became cheaper to feed his animals our snack food. In 2007 he bought enough trail mix to feed 5,000 hogs, saving $40,000. Other farmers in the U.S. Midwest were feeding their pigs and cattle cookies, licorice, cheese curls, candy bars, french fries, frosted Mini-Wheats, and Reese's Peanut Butter Cups. Near Hershey, Pennsylvania, farmers were getting waste cocoa and candy trimmings from the Hershey Company and feeding it to their cattle. Their problem has been caused by competition with crops grown directly to be turned into fuels (Figure 11.1).

FIGURE 11.1 Harvest of experimental oilseed crops at Piedmont Biofuels farm in Moncure, North Carolina.[2,3] Interest in and enthusiasm about biofuels are growing among some operating small farms, like the members of the Piedmont Biofuels Cooperative in North Carolina. Will biofuel agriculture be the wave of the future and prove environmentally sound and sustainable?

This raises the fundamental question about agriculture and the environment: For many decades world food production has exceeded demand. But the demand for food crops is growing rapidly due to a rapid rise in the standards of living of many people and continued human population growth, both of which have also increased the demand for fuels and thus competition with crops grown for biofuels. Can we find ways to feed all the people of the world without undue damage to the environment?

World food prices rose almost 40% in 2007. According to the United Nations Food and Agriculture Organization (UNFAO), in February 2008 corn prices had risen 25% and the price of wheat was 80% higher than a year before.[4] Wheat prices have reached record levels, doubling the average cost of just a few years ago, and stocks of wheat (the amount stored for future sale and use) are reaching a 30-year low, in part because of Australian droughts.[5] The FAO predicts a world food crisis, with 36 countries currently facing food crises and

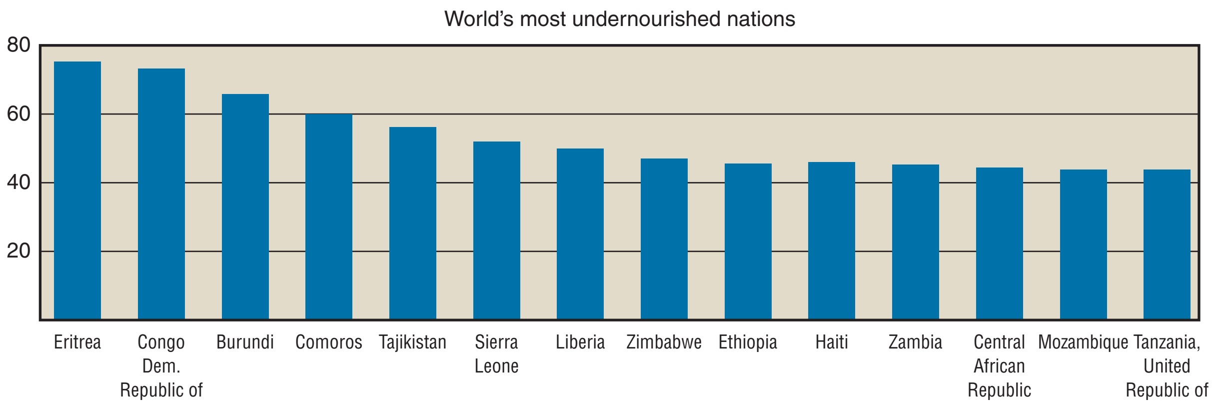


FIGURE 11.2 The world's most undernourished peoples, according to the United Nations Food and Agriculture Organization. This graph shows the 14 nations with the greatest percentage of undernourished people. Of these, 10 are in Africa. In the New World, only Haiti makes this group.[7]

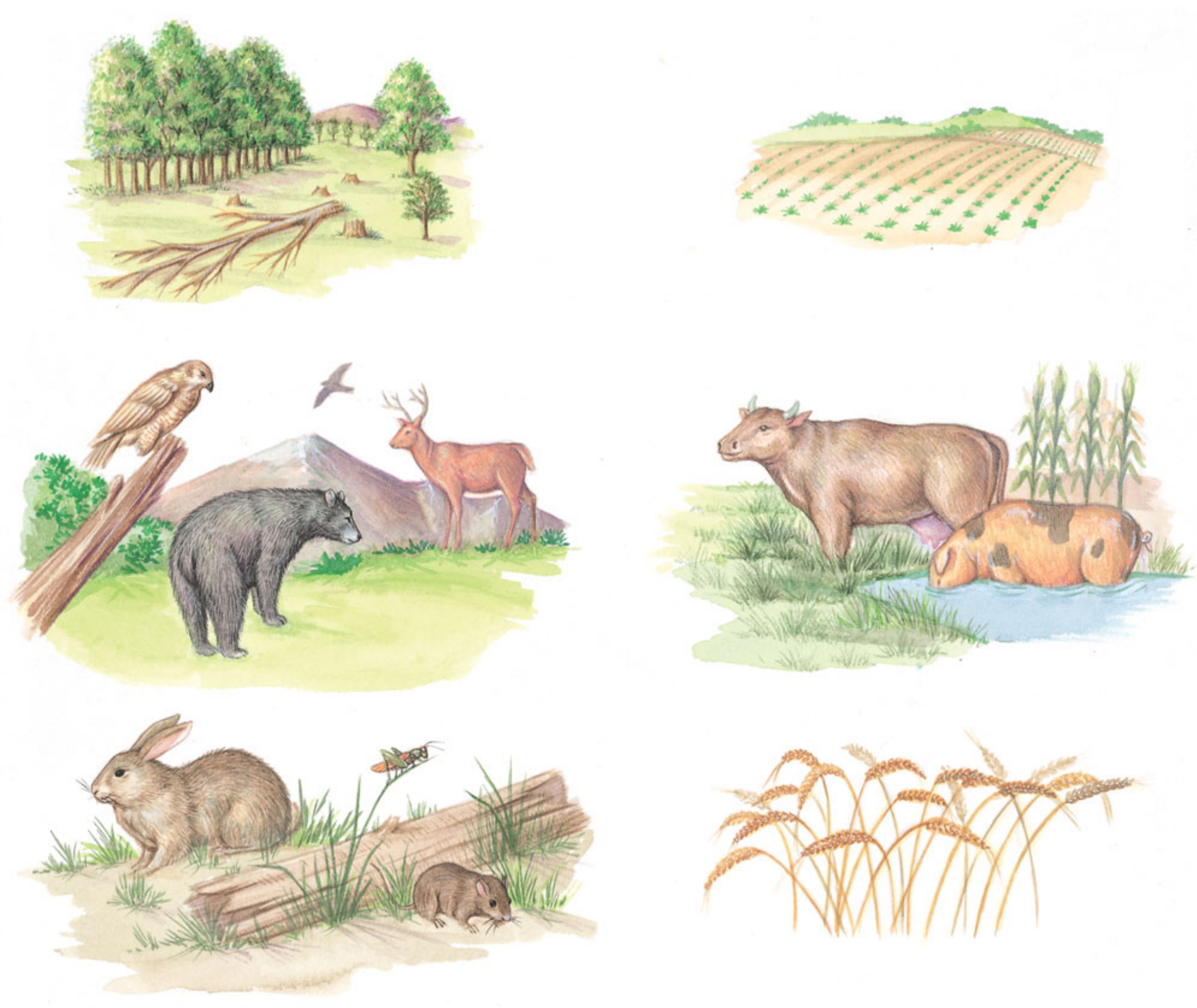
Africa leading the list with 21 nations. In the Republic of the Congo, three-quarters of the population is undernourished, and in 25 nations at least one-third of the population is undernourished, according to the UNFAO (Figure 11.2).[6]

Suddenly, people of the world need a great increase in food production, in part because of the expanding human population, in part because of competition between crops for food and crops for fuel, and in part because of droughts, floods, and other environmental impacts that have decreased agricultural production. What can be done to meet the world's growing need for food and, second to that, its need for fuel? Can agricultural production increase? By how much? And at what costs, environmental and economic?

11.1 An Ecological Perspective on Agriculture

Farming creates novel ecological conditions, referred to as **agroecosystems.** Agroecosystems differ from natural ecosystems in six ways (Figure 11.3).

Ecological succession is halted to keep the agroecosystem in an early-successional state (see Chapter 5). Most crops are early-successional species, which means that they grow fast, spread their seeds widely and rapidly, and do best when sunlight, water, and chemical nutrients in the soil are abundant. Under natural conditions, crop species would eventually be replaced by later-successional



Pre-agricultural ecosystem

Agroecosystem

FIGURE 11.3 **How farming changes an ecosystem.** It converts complex ecosystems of high structural and species diversity to a monoculture of uniform structure, and greatly modifies the soil. See text for additional information about the agricultural effects on ecosystems.

plants. Slowing or stopping natural ecological succession requires time and effort on our part.

Biological diversity and food chains are simplified.

The focus is on monoculture, one plant species rather than many. Large areas are planted with a single species or even a single strain or subspecies, such as a single hybrid of corn. The downside of monoculture is that it makes the entire crop vulnerable to attack by a single disease or a single change in environmental conditions. Repeated planting of a single species can reduce the soil content of certain essential elements, reducing overall soil fertility.

Crops are planted in neat rows and fields. These simple geometric layouts make life easy for pests because the crop plants have no place to hide. In natural ecosystems, many different species of plants grow mixed together in complex patterns, so it is harder for pests to find their favorite victims.

Agroecosystems require plowing, which is unlike any natural soil disturbance—nothing in nature repeatedly and regularly turns over the soil to a specific depth. Plowing exposes the soil to erosion and damages its physical structure, leading to a decline in organic matter and a loss of chemical elements.

They may include genetically modified crops.

FIGURE 11.4 Plowing rich prairie soil in South Dakota, around 1916, a historical photograph from the Library of Congress. The prairie had never been turned over like this.

The Plow Puzzle

There is nothing in nature like a plow, and thus there are big differences between the soils of a forest or grassland and the soils of land that has been plowed and used for crops for several thousand years. These differences were observed and written about by one of the originators of the modern study of the environment, George Perkins Marsh. Born in Vermont in the 19th century, Marsh became the U.S. ambassador to Italy and Egypt. While in Italy, he was so struck by the differences in the soils of the forests of his native Vermont and the soils that had been farmed for thousands of years on the Italian peninsula that he made this a major theme in his landmark book, *Man and Nature*, published in 1864. The farmland he observed in Italy had once been forests. While the soil in Vermont was rich in organic matter and had definite layers, the soil of Italian farmland had little organic matter and lacked definite layers.

Here's the plow puzzle: One would expect that farming that caused such major modification (see Figure 11.4) would eventually make the soils unsustainable, at least in terms of crop production, but much of the farmland in Italy and France, in China, and elsewhere, has been in continuous use since pre-Roman times and is still highly productive. How can this be? And what has been the long-term effect of such agriculture on the environment? The American Dust Bowl seemed to demonstrate how destructive plowing could be (see A Closer Look 11.1).

Deepening the plow puzzle, since the end of World War II, mechanized farming has seriously damaged more than 1 billion hectares (2.47 billion acres) of land. That's about 10.5% of the world's best soil, equal to the combined area of China and India. In addition, overgrazing and deforestation have damaged approximately 9 million hectares (22 million acres) to the point where recovery will be difficult; restoration of the rest will require serious actions.[8]

In the United States, since European settlement, about one-third of the topsoil has been lost, making 80 million hectares (198 million acres) unproductive or only marginally productive.[8] For now, think about this puzzle. We will discuss solutions to it later.

11.2 Can We Feed the World?

Can we produce enough food to feed Earth's growing human population? The answer has a lot to do with the environment and our treatment of it: Can we grow crops sustainably, so that both crop production and agricultural ecosystems remain viable? Can we produce this food without seriously damaging other ecosystems that receive the wastes of agriculture? And to these concerns we must now add: Can we produce all this

Table 11.1 LAND, PEOPLE AND AGRICULTURE, 2006

LOCATION	TOTAL LAND AREA (sq km)	HUMAN POPULATION (MILLIONS)	PEOPLE PER AREA	CROP AREA (sq km)	CROP AREA PER PERSON (sq km)	CROP LAND AS % OF TOTAL LAND
Asia	30,988,970	3,823	123.37	16,813,750	0.044	54%
Africa	29,626,570	850	28.69	11,460,700	0.135	39%
N. and C. America	21,311,580	507	23.79	6,189,030	0.122	29%
S. America	17,532,370	936	53.39	5,842,850	0.062	33%
Europe	22,093,160	362	16.39	4,836,410	0.134	22%
Australia	7,682,300	19	2.47	4,395,000	2.313	57%
World	130,043,970	6,301	48.45	49,734,060	0.079	38%

Source: FAO Statistics 2006 http://faostat.fao.org/faostat/

Note: Data are available for crops until 2003; hence, some population values in this table will differ from those elsewhere in the chapter, which are for 2005.

food and also grow crops used only to produce fuels? To answer these questions, let us begin by considering how crops grow and how productive they can be.

A surprisingly large percentage of the world's land area is in agriculture: approximately 38% (excluding Antarctica), an area about the size of South and North America combined and enough to make agriculture a human-induced biome (Table 11.1 and Figure 11.5).[9]

The history of agriculture is a series of human attempts to overcome environmental limitations and problems. Each new solution has created new environmental problems, which in turn have required their own solutions. Thus, in seeking to improve agricultural systems, we should expect some undesirable side effects and be ready to cope with them.

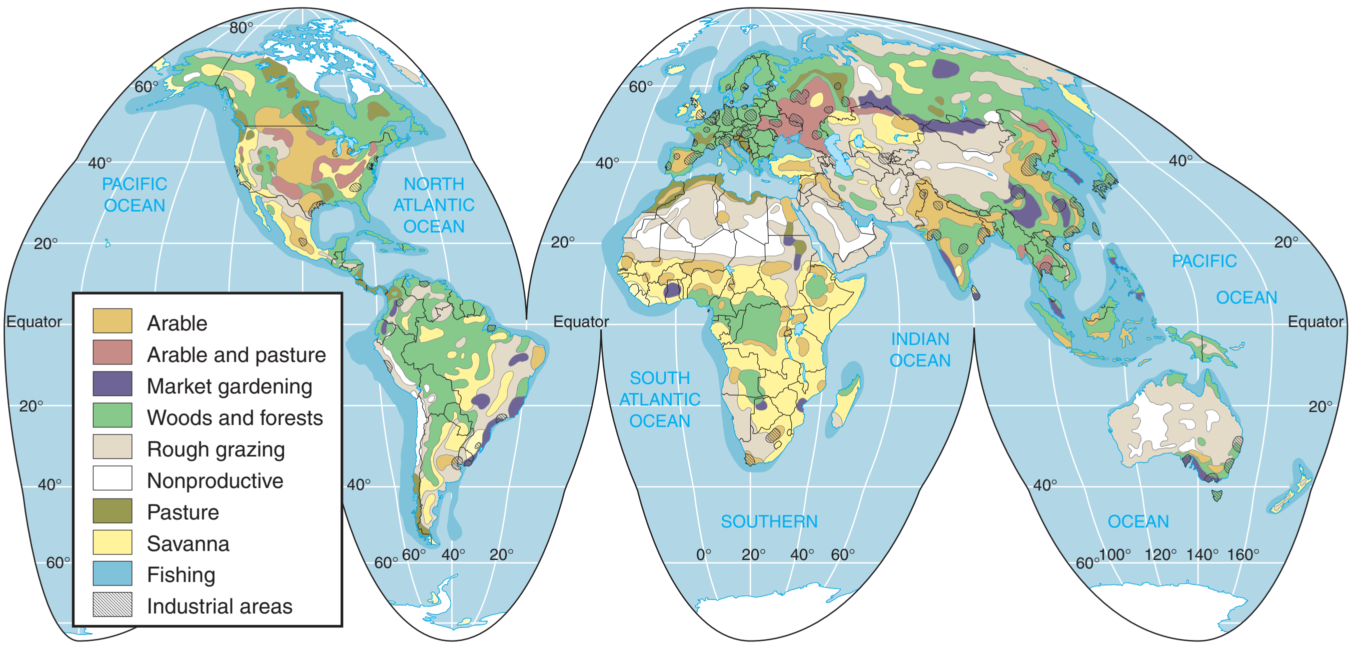


FIGURE 11.5 World land use showing arable (farmable) land. The percentage of land in agriculture varies considerably among continents, from 22% of the land in Europe to 57% in Australia. In the United States, cropland occupies 18% of the land and an additional 26% is used for pasture and rangeland, so agriculture uses 44% of the land. (*Source*: Phillips Atlas.)

The world's food supply is also greatly influenced by social disruptions and social attitudes, which affect the environment and in turn affect agriculture. In Africa, social disruptions since 1960 have included more than 20 major wars and more than 100 coups.[10] Such social instability makes sustained agricultural yields difficult—indeed, it makes any agriculture difficult if not impossible.[11] So does variation in weather, the traditional bane of farmers.[12]

How We Starve

People "starve" in two ways: undernourishment and malnourishment. World food production must provide adequate nutritional quality, not just total quantity. **Undernourishment** results from insufficient calories in available food, so that one has little or no ability to work or even move and eventually dies from the lack of energy. **Malnourishment** results from a lack of specific chemical components of food, such as proteins, vitamins, or other essential chemical elements. Widespread undernourishment manifests itself as famines that are obvious, dramatic, and fast-acting. Malnourishment is long term and insidious. Although people may not die outright, they are less productive than normal and can suffer permanent impairment and even brain damage.

Among the major problems of undernourishment are marasmus, which is progressive emaciation caused by a lack of protein and calories; kwashiorkor, which results from a lack of sufficient protein in the diet and in infants leads to a failure of neural development and thus to learning disabilities (Figure 11.6); and chronic hunger, when people have enough food to stay alive but not enough to lead satisfactory and productive lives (see Figure 11.7).

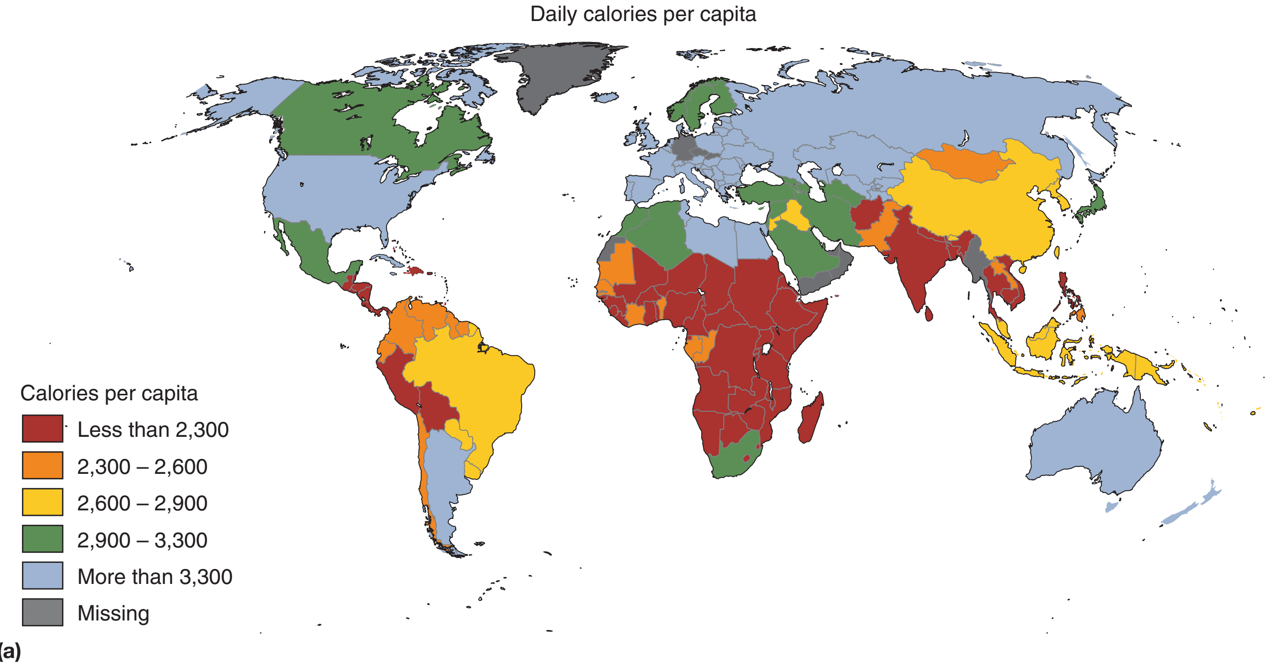
FIGURE 11.6 **Photograph of a child suffering from kwashiorkor.**

The supply of protein has been the major nutritional-quality problem. Animals are the easiest protein food source for people, but depending on animals for protein raises several questions of values. These include ecological ones (Is it better to eat lower on the food chain?), environmental ones (Do domestic animals erode soil faster than crops do?), and ethical ones (Is it morally right to eat animals?). How people answer these questions affects approaches to agriculture and thereby influences the environmental effects of agriculture. Once again, the theme of science and values arises.

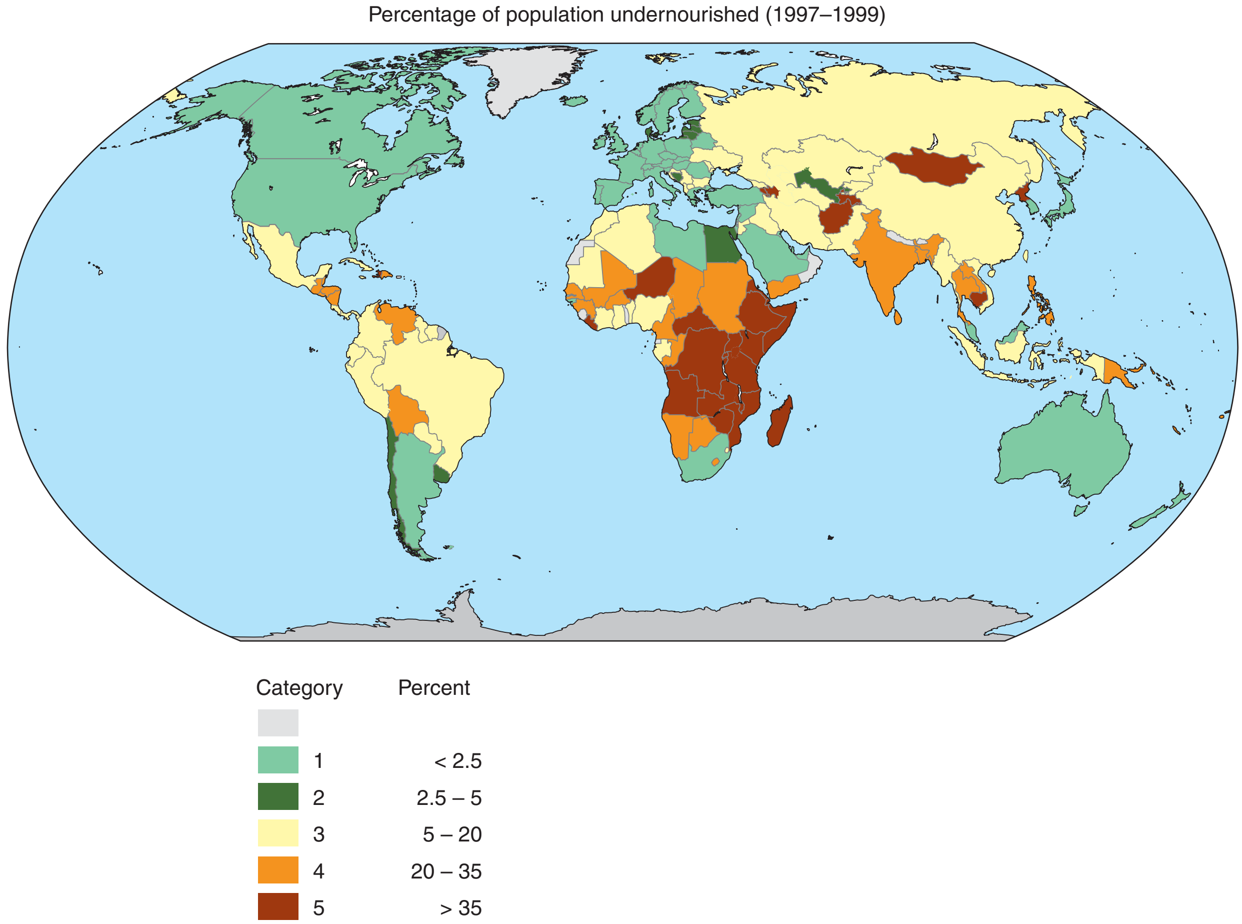
Since the end of World War II, rarely has a year passed without a famine somewhere in the world.[11] Food emergencies affected 34 countries worldwide at the end of the 20th century. Varying weather patterns in Africa, Latin America, and Asia, as well as an inadequate international trade in food, contributed to these emergencies. Examples include famines in Ethiopia (1984–1985), Somalia (1991–1993), and the 1998 crisis in Sudan. As we noted earlier, Africa remains the continent with the most acute food shortages, due to adverse weather and civil strife.[11]

A common remedy is food aid among nations, where one nation provides food to another or gives or lends money to purchase food. In the 1950s and 1960s, only a few industrialized countries provided food aid, using stocks of surplus food. A peak in international food aid occurred in the 1960s, when a total of 13.2 million tons per year of food were given. A world food crisis in the early 1970s raised awareness of the need for greater attention to food supply and stability. But during the 1980s, donor commitments totaled only 7.5 million tons. A record level of 15 million tons of food aid in 1992–1993 met less than 50% of the minimum caloric needs of the people fed. If food aid alone is to bring the world's malnourished people to a desired nutritional status, an estimated 55 million tons will be required by the year 2010—more than six times the amount available in 1995.[13]

Availability of food grown locally avoids disruptions in distribution and the need to transport food over long distances. But ironically, food aid can work against increased availability of locally grown food in regions receiving aid. Free food undercuts local farmers—they cannot compete with it. The only complete solution to famine is to develop long-term, sustainable, local agriculture. The old saying "Give a man a fish and feed him for a day; teach him to fish and feed him for life" is true.



(a)



(b)

FIGURE 11.7 **(a) Daily intake of calories worldwide. (b) Where people are undernorished.** The percentage is the portion of the country's total population that is undernourished. (*Source*: World Resources Institute Web site: http://www.wri.org/.)

11.3 What We Grow on the Land

Crops

Of Earth's half-million plant species, only about 3,000 have been used as agricultural crops and only 150 species have been cultivated on a large scale. In the United States, 200 species are grown as crops. Most of the world's food is provided by only 14 species. In approximate order of importance, these are wheat, rice, maize, potatoes, sweet potatoes, manioc, sugarcane, sugar beet, common beans, soybeans, barley, sorghum, coconuts, and bananas (Figure 11.8). Of these, six provide more than 80% of the total calories that people consume either directly or indirectly.[12]

There is a large world trade in small grains. Only the United States, Canada, Australia, and New Zealand are major exporters (see Figure 11.9); the rest of the world's nations are net importers. World small-grain production increased greatly in the second half of the 20th century, from 0.8 billion metric tons in 1961 to 1 billion in 1966, and doubled to 2 billion in 1996, a remarkable increase in 30 years. In 2005, world small-grain production was 2.2 billion tons, a record crop.[2] But production has remained relatively flat since then. The question we must ask, and cannot answer at this time, is whether this means that the world's carrying capacity for small grains has been reached or simply that the demand is not growing (Figure 11.10).

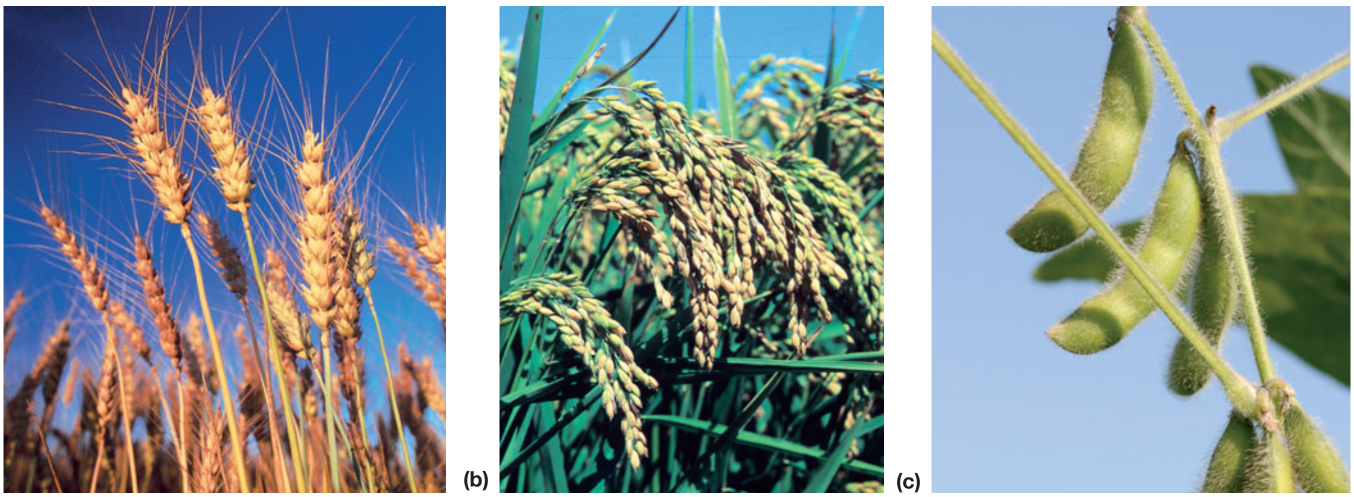
Some crops, called *forage*, are grown as food for domestic animals. These include alfalfa, sorghum, and various species of grasses grown as hay. Alfalfa is the most important forage crop in the United States, where 14 million hectares (about 30 million acres) are planted in alfalfa—one-half the world's total.

Livestock: The Agriculture of Animals

Worldwide, people keep 14 billion chickens, 1.3 billion cattle, more than 1 billion sheep, more than a billion ducks, almost a billion pigs, 700 million goats, more than 160 million water buffalo, and about 18 million camels.[18] Interestingly, the number of cattle in the world has risen slightly, by about 0.2% in the past ten years; the number of sheep has remained about the same; and the number of goats increased from 660 million in 1995 to 807 million in 2005. The production of beef, however, rose from 57 million metric tons (MT) in 1995 to 63 million MT in 2005 (the most recent date for which information is available). During the same period, the production of meat from chickens increased greatly, from 46 million MT to 70 million MT, and meat from pigs increased from 80 million MT to more than 100 million MT.[2] These are important food sources and have a major impact on the land.

Grazing on Rangelands: An Environment Benefit or Problem?

Traditional herding practices and industrialized production of domestic animals have different effects on the environment. Most cattle live on rangeland or pasture. **Rangeland** provides food for grazing and browsing animals without plowing and planting. **Pasture** is plowed, planted, and harvested to provide forage for animals. More than 34 million square kilometers (km^2) are in permanent



(a) (b) (c)

FIGURE 11.8 Among the world's major crops are (a) wheat, (b) rice, and (c) soybeans. See text for a discussion of the relative importance of these three.

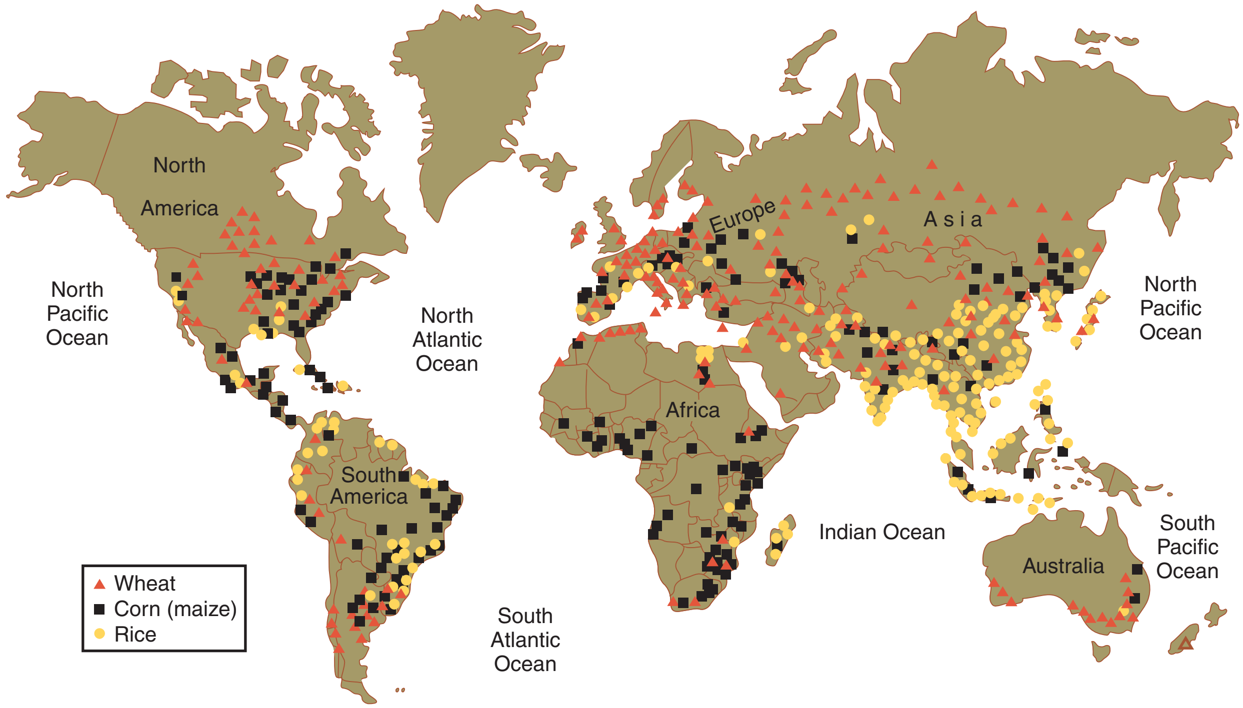


FIGURE 11.9 **Geographic distribution of world production of a few major small-grain crops.**

FIGURE 11.10 **World small-grain production since 1983**. (*Source*: FAO statistics FAOSTATS Web site.)

pasture worldwide—an area larger than the combined sizes of Canada, the United States, Mexico, Brazil, Argentina, and Chile.[2]

Almost half of Earth's land area is used as rangeland, and about 30% of Earth's land is arid rangeland, land easily damaged by grazing, especially during drought. Much of the world's rangeland is in poor condition from overgrazing. In the United States, where more than 99% of rangeland is west of the Mississippi River, rangeland conditions have improved since the 1930s, especially in upland areas. However, land near streams and the streams themselves continue to be heavily affected by grazing.

Grazing cattle trample stream banks and release their waste into stream water. Therefore, maintaining a high-quality stream environment requires that cattle be fenced behind a buffer zone. The upper Missouri River is famous for its beautiful "white cliffs," but private lands along the river that are used to graze cattle take away from the scenic splendor. The large numbers of cattle that come down to the Missouri River to drink damage

FIGURE 11.11 Cattle graze along the upper Missouri River, polluting it with their manure and increasing erosion of trampled ground near the river.

the land along the river, and the river itself runs heavy with manure (Figure 11.11). These effects extend to an area near a federally designated wild and scenic portion of the upper Missouri River, and tourists traveling on the Missouri have complained. In recent years, fencing along the upper Missouri River has increased, with small openings to allow cattle to drink, but otherwise restricting what they can do to the shoreline.

In modern industrialized agriculture, cattle are initially raised on open range and then transported to feedlots, where they are fattened for market. Feedlots have become widely known in recent years as sources of local pollution. The penned cattle are often crowded and are fed grain or forage that is transported to the feedlot. Manure builds up in large mounds and pollutes local streams when it rains. Feedlots are popular with meat producers because they are economical for rapid production of good-quality meat. However, large feedlots require intense use of resources and have negative environmental effects.

Traditional herding practices, by comparison, chiefly affect the environment through overgrazing. Goats are especially damaging to vegetation, but all domestic herbivores can destroy rangeland. The effect of domestic herbivores on the land varies greatly with their density relative to rainfall and soil fertility. At low to moderate densities, the animals may actually aid growth of aboveground vegetation by fertilizing soil with their manure and stimulating plant growth by clipping off plant ends in grazing, just as pruning stimulates plant growth. But at high densities, the vegetation is eaten faster than it can grow; some species are lost, and the growth of others is greatly reduced.

One benefit of farming animals rather than crops is that land too poor for crops that people can eat can be excellent rangeland, with grasses and woody plants that domestic livestock can eat (Figures 11.12 and 11.13). These lands occur on steeper slopes, with thinner soils or with less rainfall. Thus, from the point of view of sustainable agriculture, there is value in rangeland or pasture. The wisest approach to sustainable agriculture involves a

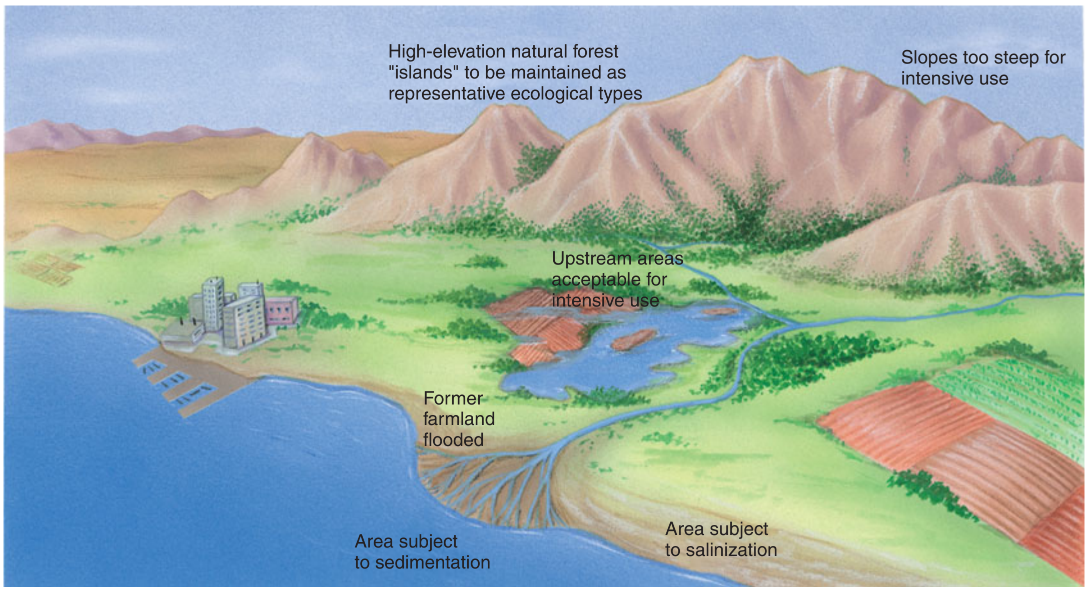


FIGURE 11.12 Physical and ecological considerations in watershed development—such as slope, elevation, floodplain, and river delta location—limit land available for agriculture.

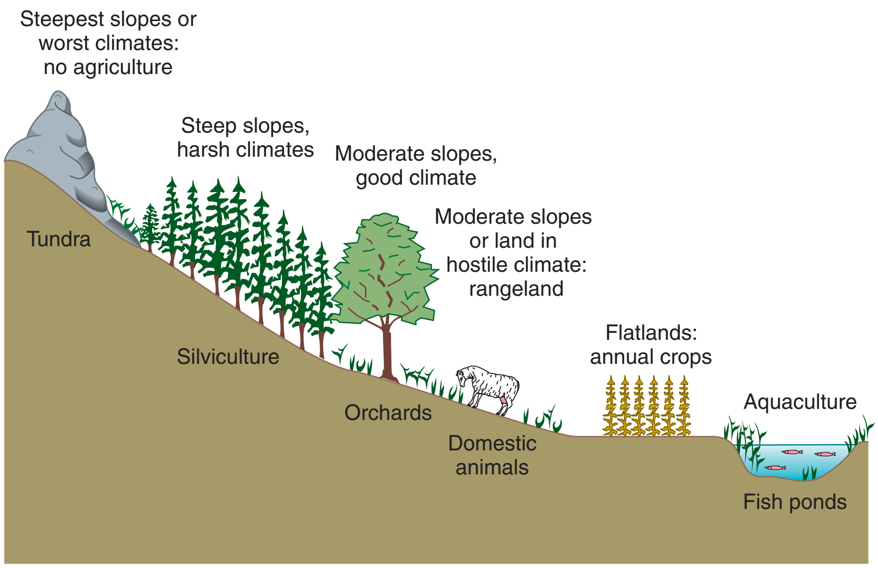


FIGURE 11.13 Land unsuitable for crop production on a sustainable basis can be used for grazing and for other purposes.

combination of different kinds of land use: using the best agricultural lands for crops, using poorer lands for pasture and rangeland.

11.4 Soils

To most of us, soils are just "dirt." But in fact soils are a key to life on the land, affecting life and affected by it. Soils develop for a very long time, perhaps thousands of years, and if you look at them closely, they are quite remarkable. You won't find anything like Earth soil on Mars or Venus or the moon. The reason is that water and life have greatly altered the land surface.

Geologically, soils are earth materials modified over time by physical, chemical, and biological processes into a series of layers. Each kind of soil has its own chemical composition. If you dig carefully into a soil so that you leave a nice, clean vertical cut, you will see the soil's layers. In a northern forest, a soil is dark at the top, then has a white powdery layer, pale as ash, then a brightly colored layer, usually much deeper than the white one and typically orangish. Below that is a soil whose color is close to that of the bedrock (which geologists call "the parent material," for obvious reasons). We call the layers *soil horizons*. The soil horizons shown in Figure 11.14 are not necessarily all present in any one soil. Very young soils may have only an upper *A* horizon over a *C* horizon, whereas mature soils may have nearly all the horizons shown.

Rainwater is slightly acid (it has a pH of about 5.5) because it has some carbon dioxide from the air dissolved in it, and this forms carbonic acid, a mild acid. As a result, when rainwater moves down into the soil, iron, calcium, magnesium, and other nutritionally important elements are leached from the upper horizons (*A* and *E*) and may be deposited in a lower horizon (*B*). The upper horizons are usually full of life and are viewed by ecologists as complex ecosystems, or ecosystem units (horizons *O* and *A*).

Within soil, decomposition is the name of the game as fungi, bacteria, and small animals live on what plants and animals on the surface produce and deposit. Bacteria and fungi, the great chemical factories of the biosphere, decompose organic compounds from the surface. Soil animals, such as earthworms, eat leaves, twigs, and other remains, breaking them into smaller pieces that are easier for the fungi and bacteria to process. In this way, the earthworms and other soil animals affect the rate of chemical reactions in the soil. There are also predators on soil animals, so there is a soil ecological food chain.

Soil *fertility* is the capacity of a soil to supply nutrients necessary for plant growth. Soils that have formed on geologically young materials are often nutrient-rich. Soils in humid areas and tropics may be heavily leached and relatively nutrient-poor due to the high rainfall. In such soils, nutrients may be cycled through the organic-rich upper horizons; and if forest cover is removed, reforestation may be very difficult. Soils that accumulate certain clay minerals in semiarid regions may swell when they get wet and shrink as they dry out, cracking roads, walls, buildings, and other structures. Expansion and contraction of soils in the United States cause billions of dollars' worth of property damage each year.

Coarse-grained soils, especially those composed primarily of sand, are particularly susceptible to erosion by water and wind. Sand and gravel have relatively large spaces between grains, so water moves through them quickly. Soils with small clay particles retain water well and retard the movement of water. Soils with a mixture of clay and sand can retain water well enough for plant growth but also drain well. Soils with a high percentage of organic

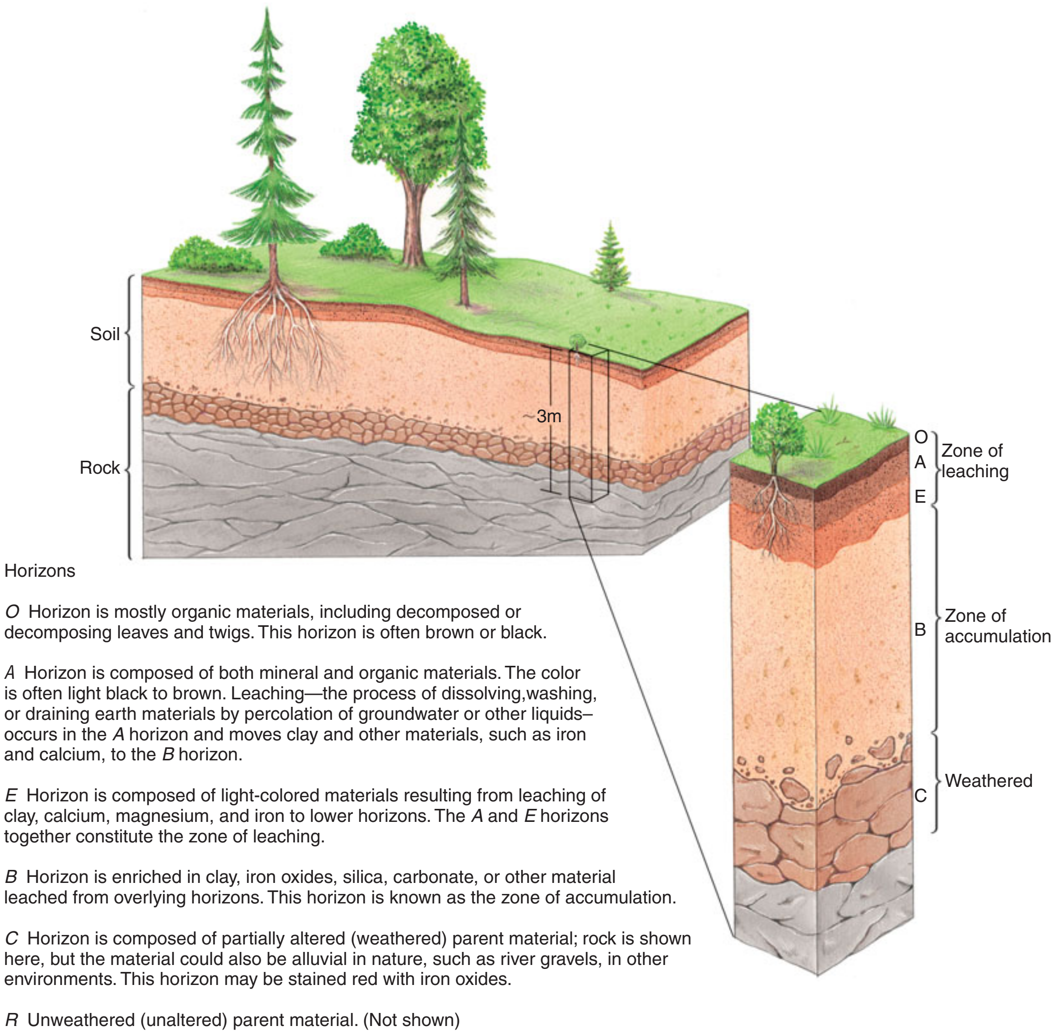


FIGURE 11.14 Idealized diagram of a soil, showing soil horizons.

matter also retain water and chemical nutrients for plant growth. It is an advantage to have good drainage, so a coarse-grained soil is a good place to build your house. If you are going to farm, you'll do best in a loam soil, which has a mixture of particle sizes.

Restoring Our Soils

Part of the answer to the plow puzzle that we discussed earlier in this chapter is the application of organic and inorganic fertilizer. Another part of the answer is general improvements in how plowing is done and where.

Because of improved farming practices, soil erosion has slowed 40% in the United States. According to the U.S. Department of Agriculture, "water (sheet & rill) erosion on cropland dropped from 4.0 tons per acre per year in 1982 to 2.6 tons per acre per year in 2003; wind erosion rates dropped from 3.3 to 2.1 tons per acre per year."[14]

One outstanding example is the drainage area of Coon Creek, Wisconsin, an area of 360 km^2 that has been heavily farmed for more than a century. This stream's watershed was the subject of a detailed study in the 1930s by the U.S. Soil Conservation Service, and was then restudied in the 1970s and 1990s. Measurements at these three times showed that soil erosion was only 6% of what it had been in the 1930s.[15] The bad news is that, even so, the soil is eroding faster than new soil is being generated.[16]

Fertilizers

Traditionally, farmers combated the decline in soil fertility by using organic fertilizers, such as animal manure, which improve both chemical and physical characteristics of soil. But organic fertilizers have drawbacks, especially under intense agriculture on poor soils. In such situations, they do not provide enough of the chemical elements needed to replace what is lost.

A CLOSER LOOK 11.1

The Great American Dust Bowl

Soil erosion became a national issue in the United States in the 1930s, when intense plowing, combined with a major drought, loosened the soil over large areas. The soil blew away, creating dust storms that buried automobiles and houses, destroyed many farms, impoverished many people, and led to a large migration of farmers from Oklahoma and other western and midwestern states to California. The human tragedies of the Dust Bowl were made famous by John Steinbeck's novel *The Grapes of Wrath,* later a popular movie starring Henry Fonda (Figure 11.15).

The land that became the Dust Bowl had been part of America's great prairie, where grasses rooted deep, creating a heavily organic soil a meter or more down. The dense cover provided by grass stems and the anchoring power of roots protected the soil from the erosive forces of water and wind. When the plow turned over those roots, the soil was exposed directly to sun, rain, and wind, which further loosened the soil.

FIGURE 11.15 The Dust Bowl. Poor agricultural practices and a major drought created the Dust Bowl, which lasted about ten years during the 1930s. Heavily plowed lands lacking vegetative cover blew away easily in the dry winds, creating dust storms and burying houses.

The development of industrially produced fertilizers, commonly called "chemical" or "artificial" fertilizers, was a major factor in greatly increasing crop production in the 20th century. One of the most important advances was the invention of industrial processes to convert molecular nitrogen gas in the atmosphere to nitrate that can be used directly by plants. Phosphorus, another biologically important element, is mined, usually from a fossil source that was biological in origin, such as deposits of bird guano on islands used for nesting (Figure 11.16). The scientific-industrial age brought with it mechanized mining of phosphates and their long-distance transport, which, at a cost, led to short-term increases in soil fertility. Nitrogen, phosphorus, and other elements are combined in proportions appropriate for specific crops in specific locations.

Limiting Factors

Crops require about 20 chemical elements. These must be available in the right amounts, at the right times, and in the right proportions to each other. It is customary to divide these life-important chemical elements into two groups, macronutrients and micronutrients. A **macronutrient** is a chemical element required by all living things in relatively large amounts. Macronutrients are sulfur, phosphorus, magnesium, calcium, potassium, nitrogen, oxygen, carbon, and hydrogen. A **micronutrient** is a chemical element required in small amounts—either in extremely small amounts by all forms of life or in moderate to small amounts for some forms of life. Micronutrients are often rarer metals, such as molybdenum, copper, zinc, manganese, and iron.

High-quality agricultural soil has all the chemical elements required for plant growth and also has a physical structure that lets both air and water move freely through the soil and yet retain water well. The best agricultural soils have a high organic content and a mixture of sediment particle sizes. Lowland rice grows in flooded ponds and requires a heavy, water-saturated soil, while watermelons grow best in very sandy soil. Soils rarely have everything a crop needs. The question for a farmer is: What needs to be added or done to make a soil more productive for a crop? The traditional answer is that, at any time, just one factor is limiting. If that **limiting factor** can be improved, the soil will be more productive; if that single factor is not improved, nothing else will make a difference.

The idea that some single factor determines the growth and therefore the presence of a species is known as **Liebig's law of the minimum**, after Justus von Liebig, a 19th-century agriculturalist credited with first stating this idea. A general statement of Liebig's law is: The growth of a plant is affected by one limiting factor at a time—the one whose availability is the least in comparison to the needs of a plant.

FIGURE 11.16 Boobies on a guano island stand on centuries of bird droppings. The birds feed on ocean fish and nest on islands. In dry climates, their droppings accumulate, becoming a major source of phosphorus for agriculture for centuries.

Striking cases of soil-nutrient limitations have been found in Australia—which has some of the oldest soils in the world—on land that has been above sea level for many millions of years, during which time severe leaching has taken place. Sometimes trace elements are required in extremely small amounts. For example, it is estimated that in certain Australian soils adding an ounce of molybdenum to a field increases the yield of grass by 1 ton/year. The idea of a limiting growth factor, originally used in reference to crop plants, has been extended by ecologists to include all life requirements for all species in all habitats.

If Liebig were always right, then environmental factors would always act one by one to limit the distribution of living things. But there are exceptions. For example, nitrogen is a necessary part of every protein, and proteins are essential building blocks of cells. Enzymes, which make many cell reactions possible, contain nitrogen. A plant given little nitrogen and phosphorus might not make enough of the enzymes involved in taking up and using phosphorus. Increasing nitrogen to the plant might therefore increase the plant's uptake and use of phosphorus. If this were so, the two elements would have a **synergistic effect**, in which a change in the availability of one resource affects the response of an organism to some other resource.

So far we have discussed the effects of chemical elements when they are in short supply. But it is also possible to have too much of a good thing—most chemical elements become toxic in concentrations that are too high. As a simple example, plants die when they have too little water but also when they are flooded, unless they have specific adaptations to living in water. So it is with chemical elements required for life.

11.5 Controlling Pests

From an ecological point of view, pests are undesirable competitors, parasites, or predators. The major agricultural pests are insects that feed mainly on the live parts of plants, especially leaves and stems; nematodes (small worms), which live mainly in the soil and feed on roots and other plant tissues; bacterial and viral diseases; weeds (plants that compete with the crops); and vertebrates (mainly rodents and birds) that feed on grain or fruit. Even today, with modern technology, the total losses from all pests are huge; in the United States, pests account for an estimated loss of one-third of the potential harvest and about one-tenth of the harvested crop. Preharvest losses are due to competition from weeds, diseases, and herbivores; postharvest losses are largely due to herbivores.[17]

Because a farm is maintained in a very early stage of ecological succession and is enriched by fertilizers and water, it is a good place not only for crops but also for other early-successional plants. These noncrop and therefore undesirable plants are what we call weeds. A weed is just a plant in a place we do not want it to be. There are about 30,000 species of weeds, and in any year a typical farm field is infested with between 10 and 50 of them. Some weeds can have a devastating effect on crops. For example, the production of soybeans is reduced by 60% if a weed called cocklebur grows three individuals per meter (one individual per foot).[18]

Pesticides

Before the Industrial Revolution, farmers could do little to prevent pests except remove them or use farming methods that tended to decrease their density. Pre-industrial farmers planted aromatic herbs and other vegetation that repels insects.

The scientific industrial revolution brought major changes in agriculture pest control, which we can divide into four stages:

Stage 1: Broad-Spectrum Inorganic Toxins

With the beginning of modern science-based agriculture, people began to search for chemicals that would reduce the abundance of pests. Their goal was a "magic bullet"—a chemical (referred to as a narrow-spectrum pesticide) that would have a single target, just one pest, and not affect anything else. But this proved elusive. The earliest pesticides were simple inorganic compounds that were widely toxic. One of the earliest was arsenic, a chemical element toxic to all life, including people. It was certainly effective in killing pests, but it killed beneficial organisms as well and was very dangerous to use.

Stage 2: Petroleum-Based Sprays and Natural Plant Chemicals (1930s on)
Many plants produce chemicals as a defense against disease and herbivores, and these chemicals are effective pesticides. Nicotine, from the tobacco plant, is the primary agent in some insecticides still widely used today. However, although natural plant pesticides are comparatively safe, they were not as effective as desired.

Stage 3: Artificial Organic Compounds
Artificial organic compounds have created a revolution in agriculture, but they have some major drawbacks (see Risk–Benefit Analysis in Chapter 7). One problem is secondary pest outbreaks, which occur after extended use (and possibly because of extended use) of a pesticide. Secondary pest outbreaks can come about in two ways: (1) Reducing one target species reduces competition with a second species, which then flourishes and becomes a pest, or (2) the pest develops resistance to the pesticides through evolution and natural selection, which favor those who have a greater immunity to the chemical. Resistance has developed to many pesticides. For example, Dasanit (fensulfothion), an organophosphate first introduced in 1970 to control maggots that attack onions in Michigan, was originally successful but is now so ineffective that it is no longer used for that crop.

Some artificial organic compounds, such as DDT, are broad-spectrum, but more effective than natural plant chemicals. However, they also have had unexpected environmental effects. For example, aldrin and dieldrin have been widely used to control termites as well as pests on corn, potatoes, and fruits. Dieldrin is about 50 times as toxic to people as DDT. These chemicals are designed to remain in the soil and typically do so for years. Therefore, they have spread widely.

World use of pesticides exceeds 2.5 billion kg (5 billion pounds), and in the United States it exceeds 680 million kg (1,200 million pounds) (Figure 11.17). The total amount paid for these pesticides is \$32 billion worldwide and \$11 billion in the United States.[12] But the magic bullet has remained elusive. Once applied, these chemicals may decompose in place or may be blown by the wind or transported by surface and subsurface waters, meanwhile continuing to decompose. Sometimes the initial breakdown products (the first, still complex chemicals produced from the original pesticides) are toxic, as is the case with DDT. Eventually, the toxic compounds are decomposed to their original inorganic or simple, nontoxic organic compounds, but for some chemicals this can take a very long time.

Public-health standards and environmental-effects standards have been established for some of these compounds. The United States Geological Survey has established a network for monitoring 60 sample watersheds throughout the nation. These are medium-size watersheds, not the entire flow from the nation's major rivers. One such watershed is that of the Platte River, a major tributary of the Missouri River.

The most common herbicides used for growing corn, sorghum, and soybeans along the Platte River were alachlor, atrazine, cyanazine, and metolachlor, all organonitrogen herbicides. Monitoring of the Platte near Lincoln, Nebraska, suggested that during heavy spring runoff, concentrations of some herbicides might be reaching or exceeding established public-health standards. But this research is just beginning, and it is difficult to reach definitive conclusions as to whether present concentrations are causing harm in public water supplies or to wildlife, fish, algae in freshwater, or vegetation. Advances in knowledge give us much more information, on a more regular basis, about how much of many artificial compounds are in our waters, but we are still unclear about their environmental effects. A wider and better program to monitor pesticides in water and soil is important to provide a sound scientific basis for dealing with pesticides.

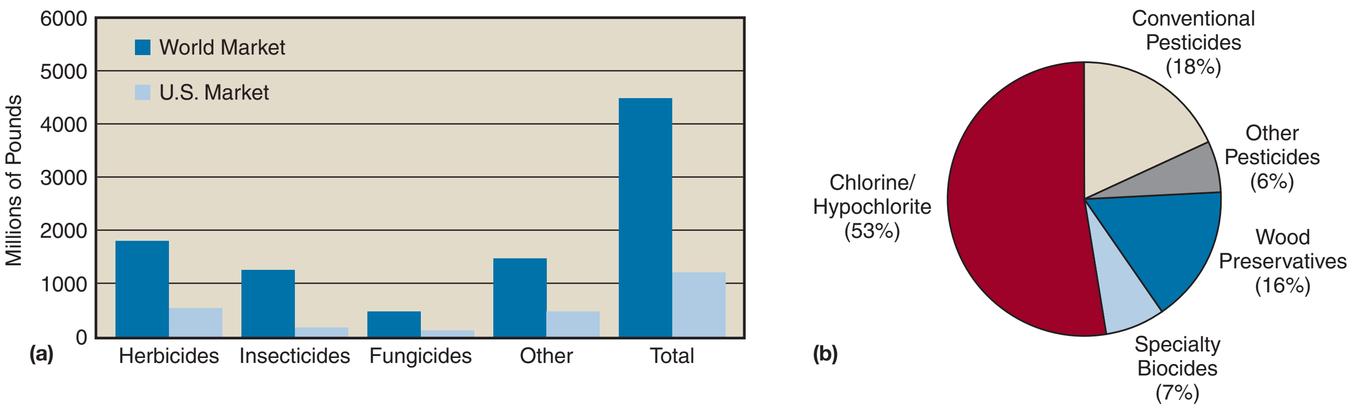


FIGURE 11.17 **World use of pesticides**. **(a)** Total amounts, **(b)** percentage by main type. (*Sources*: EPA [2006]."2000–2001Pesticide Market Esimates: Usage.")

Stage 4: Integrated Pest Management and Biological Control

Integrated pest management (IPM) uses a combination of methods, including biological control, certain chemical pesticides, and some methods of planting crops (Figure 11.18). A key idea underlying IPM is that the goal can be control rather than complete elimination of a pest. This is justified for several reasons. Economically, it becomes more and more expensive to eliminate a greater and greater percentage of a pest, while the value of ever-greater elimination, in terms of crops to sell, becomes less and less. This suggests that it makes economic sense to eliminate only enough to provide benefit and leave the rest. In addition, allowing a small but controlled portion of a pest population to remain does less damage to ecosystems, soils, water, and air.

Integrated pest management also moves away from monoculture growing in perfectly regular rows. Studies have shown that just the physical complexity of a habitat can slow the spread of parasites. In effect, a pest, such as a caterpillar or mite, is trying to find its way through a maze. If the maze consists of regular rows of nothing but what the pest likes to eat, the maze problem is easily solved by the dumbest of animals. But if several species, even two or three, are arranged in a more complex pattern, pests have a hard time finding their prey.

No-till or low-till agriculture is another feature of IPM because this helps natural enemies of some pests to build up in the soil, whereas plowing destroys the habitats of these enemies.

Biological control includes using one species that is a natural enemy of another. One of the most effective is the bacterium ***Bacillus thuringiensis***, known as BT, which causes a disease that affects caterpillars and the larvae of other insect pests. Spores of BT are sold commercially—you can buy them at your local garden store and use them in your home garden. BT has been one of the most important ways to control epidemics of gypsy moths, an introduced moth whose larvae periodically strip most of the leaves from large areas of forests in the eastern United States. BT has proved safe and effective—safe because it causes disease only in specific insects and is harmless to people and other mammals, and because, as a natural biological "product," its presence and its decay are nonpolluting.

Another group of effective biological-control agents are small wasps that are parasites of caterpillars. Control of the oriental fruit moth, which attacks a number of fruit crops, is an example of IPM biological control. The moth was found to be a prey of a species of wasp, *Macrocentrus ancylivorus*, and introducing the wasp into fields helped control the moth. Interestingly, in peach fields the wasp was more effective when strawberry fields were nearby. The strawberry fields provided an alternative habitat for the wasp, especially important for overwintering.[9] As this example shows, spatial complexity and biological diversity also become parts of the IPM strategy.

In the list of biological-control species we must not forget ladybugs, which are predators of many pests. You can buy these, too, at many garden stores and release them in your garden.

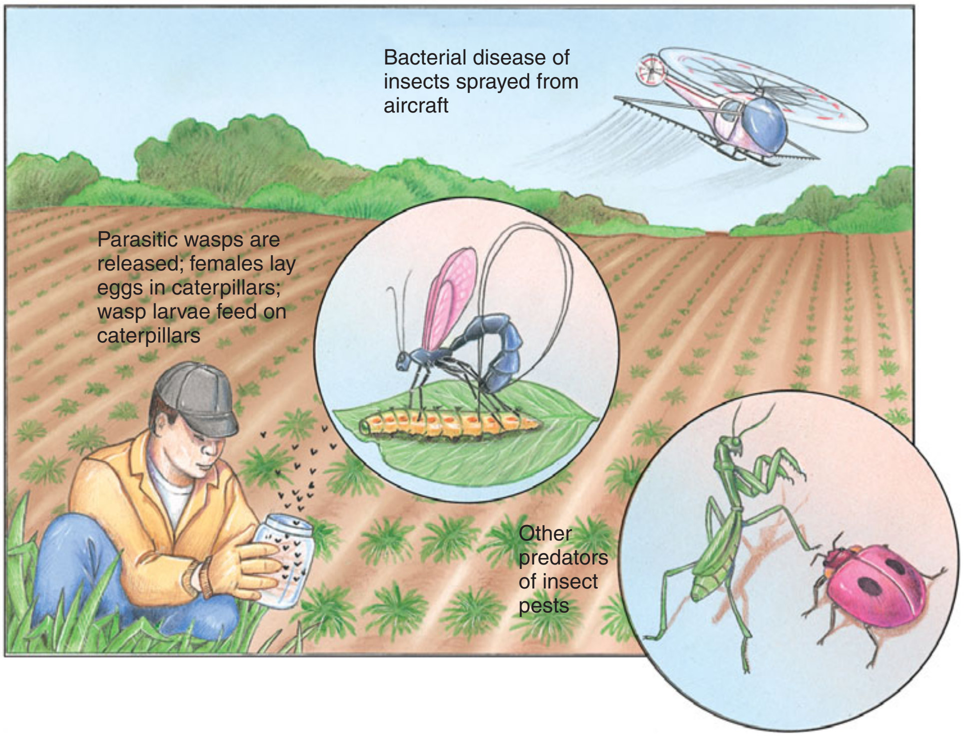


FIGURE 11.18 Integrated pest management. The goal is to reduce the use of artificial pesticides, reduce costs, and efficiently control pests.

Another biological control uses sex pheromones, chemicals released by most species of adult insects (usually the female) to attract members of the opposite sex. In some species, pheromones have been shown to be effective up to 4.3 km (2.7 mi) away. These chemicals have been identified, synthesized, and used as bait in insect traps, in insect surveys, or simply to confuse the mating patterns of the insects involved.

While biological control works well, it has not solved all problems with agricultural pests. As for artificial pesticides, although they are used in integrated pest management, they are used along with the other techniques, so the application of these pesticides can be sparing and specific. This would also greatly reduce the costs to farmers for pest control.

11.6 The Future of Agriculture

Today, there are three major technological approaches to agriculture. One is modern mechanized agriculture, where production is based on highly mechanized technology that has a high demand for resources—including land, water, and fuel—and makes little use of biologically-based technologies. Another approach is resource-based—that is, agriculture based on biological technology and conservation of land, water, and energy. An offshoot of this second approach is organic food production—growing crops without artificial chemicals (including pesticides) or genetic engineering but instead using ecological control methods. The third approach is genetic engineering.

In mechanized agriculture, production is determined by economic demand and limited by that demand, not by resources. In resource-based agriculture, production is limited by environmental sustainability and the availability of resources, and economic demand usually exceeds production.

With these methods in mind, we can consider what can be done to help crop production keep pace with human population growth. Here are some possibilities.

Increased Production per Acre

Some agricultural scientists and agricultural corporations believe that production per unit area will continue to increase, partially through advances in genetically modified crops. This new methodology, however, raises some important potential environmental problems, which we will discuss later. Furthermore, increased production in the past has depended on increased use of water and fertilizers. Water is a limiting factor in many parts of the world and will become a limiting factor in more areas in the future.

Increased Farmland Area

A United Nations Food and Agriculture Organization conference held in early 2008 considered the coming world food crisis. It was reported that 23 million hectares (more than 46 million acres) of farmland had been withdrawn from production in Eastern Europe and the Commonwealth of Independent States (CIS) region, especially in countries such as Kazakhstan, Russia, and Ukraine, and that at least half—13 million hectares (15 million acres)—could be readily put back into production with little environmental effect.[19] This would be like adding all the farmland in Iowa, Illinois, and Indiana.[20]

The need for additional farmland brings up, once again, the problem that agrifuels bring to agriculture: taking land away from food production to produce fuels instead.

New Crops and Hybrids

Since there are so many plant species, perhaps some yet unused ones could provide new sources of food and grow in environments little used for agriculture. Those interested in conserving biological diversity urge a search for such new crops on the grounds that this is one utilitarian justification for the conservation of species. It is also suggested that some of these new crops may be easier on the environment and therefore more likely to allow sustainable agriculture. But it may be that over the long history of human existence those species that are edible have already been found, and the number is small. Research is under way to seek new crops or plants that have been eaten locally but whose potential for widespread, intense cultivation has not been tested.

Among the likely candidates for new crops are amaranth for seeds and leaves; *Leucaena*, a legume useful for animal feed; and triticale, a synthetic hybrid of wheat and rye.[21] A promising source of new crops is the desert; none of the 14 major crops are plants of arid or semiarid regions, yet there are vast areas of desert and semidesert. The United States has 200,000 million hectares (about 500,000 million acres) of arid and semiarid rangeland. In Africa, Australia, and South America, the areas are even greater. Several species of plants can be grown commercially under arid conditions, allowing us to use a biome for agriculture that has been little used in this way in the past. Examples of these species are guayule (a source of rubber), jojoba (for oil), bladderpod (for oil from seeds), and gumweed (for resin). Jojoba, a native shrub of the American Sonoran Desert, produces an extremely fine oil, remarkably resistant to bacterial degradation, which is useful in cosmetics and as a fine lubricant. Jojoba is now grown commercially in Australia, Egypt, Ghana, Iran, Israel, Jordan, Mexico, Saudi Arabia, and the United States.[22] Although these examples are not food crops, they release other lands, now used to produce similar products, to grow food.

FIGURE 11.19 Experimental rice plots at the International Rice Research Institute, Philippines, showing visual crop variation based on the use of fertilizers.

Among the most successful developments of new hybrids have been those developed by the **green revolution**, the name attached to post–World War II programs that have led to the development of new strains of crops with higher yields, better resistance to disease, or better ability to grow under poor conditions. These crops include superstrains of rice (at the International Rice Research Institute in the Philippines) (see Figure 11.19) and strains of maize with improved disease resistance (at the International Maize and Wheat Improvement Center in Mexico).

Better Irrigation

Drip irrigation—from tubes that drip water slowly—greatly reduces the loss of water from evaporation and increases yield. However, it is expensive and thus most likely to be used in developed nations or nations with a large surplus of hard currency—in other words, in few of the countries where hunger is most severe.

Organic Farming

Organic farming is typically considered to have three qualities: It is more like natural ecosystems than monoculture; it minimizes negative environmental impacts; and the food that results from it does not contain artificial compounds. According to the U.S. Department of Agriculture (USDA), organic farming has been one of the fastest-growing sectors in U.S. agriculture, although it still occupies a small fraction of U.S. farmland and contributes only a small amount of agriculture income. By the end of the 20th century it amounted to about $6 billion—much less than the agricultural production of California.

In the 1990s, the number of organic milk cows rose from 2,300 to 12,900, and organic layer hens increased from 44,000 to more than 500,000. In the United States only 0.01% of the land planted in corn and soybeans used certified organic farming systems in the mid-1990s; about 1% of dry peas and tomatoes were grown organically, and about 2% of apples, grapes, lettuce, and carrots. On the high end, nearly one-third of U.S. buckwheat, herb, and mixed vegetable crops were grown under organic farming conditions.[23] USDA certification of organic farming became mandatory in 2002. After that, organic cropland that was listed as certified more than doubled, and the number of farmers certifying their products rose 40%. In the United States today, more than 1.3 million acres are certified as organic. There are about 12,000 organic farmers in the United States, and the number is growing 12% per year.[24]

Eating Lower on the Food Chain

Some people believe it is ecologically unsound to use domestic animals as food, on the grounds that eating each step farther up a food chain leaves much less food to eat per acre. This argument is as follows: No organism is 100% efficient; only a fraction of the energy in food taken in is converted to new organic matter. Crop plants may convert 1–10% of sunlight to edible food, and cows may convert only 1–10% of hay and grain to meat. Thus, the same area could produce 10 to 100 times more vegetation than meat per year. This holds true for the best agricultural lands, which have deep, fertile soils on level ground.

11.7 Genetically Modified Food: Biotechnology, Farming, and Environment

The discovery that DNA is the universal carrier of genetic information has led to development and use of genetically modified crops, which has given rise to new environmental controversies as well as a promise of increased agricultural production.

Genetic engineering in agriculture involves several different practices, which we can group as follows: (1) faster and more efficient ways to develop new hybrids; (2) introduction of the "terminator gene"; and (3) transfer of genetic properties from widely divergent kinds of life. These three practices have quite different potentials and problems. We need to keep in mind a general rule of environmental actions, the rule of natural change: If actions we take are similar in kind and frequency to natural changes, then the effects on the environment are likely to be benign. This is because species have had a long time to evolve and adapt to these changes. In contrast, changes that are novel—that do not occur in nature—are more likely to have negative or undesirable environmental effects, both direct and indirect. We can apply this rule to the three categories of genetically engineered crops.

The jury is out as to whether the benefits of genetically modified crops will outweigh undesirable effects. As with many new technologies of the industrial age, application has preceded environmental investigation and understanding, and the widespread use of **genetically modified crops** (GMCs) is under way before the environmental effects are well understood. The challenge for environmental science is to gain an understanding of environmental effects of GMCs quickly.

New Hybrids

The development of hybrids within a species is a natural phenomenon, and the development of hybrids of major crops, especially of small grains, has been a major factor in the great increase in productivity of 20th-century agriculture. So, strictly from an environmental perspective, genetic engineering to develop hybrids within a species is likely to be as benign as the development of agricultural hybrids has been with conventional methods.

There is an important caveat, however. Some people are concerned that the great efficiency of genetic modification methods may produce "superhybrids" that are so productive they can grow where they are not wanted and become pests. There is also concern that some of the new hybrid characteristics could be transferred by interbreeding with closely related weeds. This could inadvertently create a "superweed" whose growth, persistence, and resistance to pesticides would make it difficult to control. Another environmental concern is that new hybrids might be developed that could grow on more and more marginal lands. Raising crops on such marginal lands might increase erosion and sedimentation and lead to decreased biological diversity in specific biomes. Still another potential problem is that "superhybrids" might require much more fertilizer, pesticide, and water. This could lead to greater pollution and the need for more irrigation.

On the positive side, genetic engineering could lead to hybrids that require less fertilizer, pesticide, and water. For example, right now only legumes (peas and their relatives) have symbiotic relationships with bacteria and fungi that allow them to fix nitrogen. Attempts are under way to transfer this capability to other crops, so that more kinds of crops would enrich the soil with nitrogen and require much less external application of nitrogen fertilizer.

The Terminator Gene

The **terminator gene** makes seeds from a crop sterile. This is done for environmental and economic reasons. In theory, it prevents a genetically modified crop from spreading. It also protects the market for the corporation that developed it: Farmers cannot avoid purchasing seeds by using some of their crops' hybrid seeds the next year. But this poses social and political problems. Farmers in less-developed nations, and governments of nations that lack genetic-engineering capabilities, are concerned that the terminator gene will allow the United States and a few of its major corporations to control the world food supply. Concerned observers believe that farmers in poor nations must be able to grow next year's crops from their own seeds because they cannot afford to buy new seeds every year. This is not directly an environmental problem, but it can become an environmental problem indirectly by affecting total world food production, which then affects the human population and how land is used in areas that have been in agriculture.

Transfer of Genes from One Major Form of Life to Another

Most environmental concerns have to do with the third kind of genetic modification of crops: the transfer of genes from one major kind of life to another. This is a novel effect and, as we have explained, therefore more likely to have undesirable results. In several cases, in fact, this type of genetic modification has affected the environment in unforeseen and undesirable ways. Perhaps the best-known involves potatoes and corn, caterpillars that eat these crops, a disease of caterpillars that controls these pests, and an endangered species, monarch butterflies. Here is what happened.

As discussed earlier, the bacterium *Bacillus thuringiensis* is a successful pesticide that causes a disease in many caterpillars. With the development of biotechnology, agricultural scientists studied the bacteria and discovered the toxic chemical and the gene that caused its production within the bacteria. This gene was then transferred to potatoes and corn so that the biologically engineered plants produced their own pesticide. At first, this was believed to be a constructive step in pest control because it was no longer necessary to spray a pesticide. However, the genetically engineered potatoes and corn produced the toxic BT substance in every cell—not just in the leaves that the caterpillars ate, but also in the potatoes and corn sold as food, in the flowers, and in the pollen. This has a potential, not yet demonstrated, to create problems for species that are not intended targets of the BT (Figure 11.20).

A strain of rice has been developed that produces beta-carotene, important in human nutrition. The rice thus has added nutritional benefits that are particularly valuable for the poor of the world who depend on rice as a primary food. The gene that enables rice to make beta-carotene comes from daffodils, but the modification actually required the introduction of four specific genes and would likely be impossible without genetic-engineering techniques. That is, genes were transferred between plants that would not exchange genes in nature. Once again, the rule of natural change suggests that we should monitor such actions carefully. Indeed, although the genetically modified rice appears to have beneficial effects, the government of India has refused to allow it to be grown in that country.[15]

There is much concern worldwide about the political, social, and environmental effects of genetic modification of crops. This is a story in process, one that will change rapidly in the next few years. You can check on these fast-moving events on the textbook's Web site.

(a)


Bacillus thuringiensis bacteria (a natural pecticide). The gene that caused the pecticide (BT) was placed in corn through genetic engineering.

(b)


BT corn contains its own pesticide in every cell of the plant.

(c)


Pollen from the BT corn is also toxic and when it lands on milkweed, monarch butterflies that eat the milkweed may die.

FIGURE 11.20 The flow of the BT toxin from bacteria **(a)** to corn through genetic engineering **(b)** and the possible ecological transfer of toxic substances to monarch butterflies **(c)**.

11.8 Aquaculture

In contrast to food obtained on land, we still get most of our marine and freshwater food by hunting. Hunting wild fish has not been sustainable (see Chapter 13), and thus **aquaculture**, the farming of this important source of protein in both marine and freshwater habitats, is growing rapidly and could become one of the major ways to provide food of high nutritional quality. Popular aquacultural animals include carp, tilapia, oysters, and shrimp, but in many nations other species are farm-raised and culturally important, such as yellowtail (important in Japan and perhaps just one of several species); crayfish (United States); eels and minnows (China); catfish (southern and midwestern United States); salmon (Canada, Chile, Norway, and the United States); trout (United States); plaice, sole, and the Southeast Asian milkfish (Great Britain); mussels (Canada, France, Spain, and Southeast Asian countries); and sturgeon (Ukraine). A few species—trout and carp—have been subject to genetic breeding programs.[25]

Although relatively new in the United States, aquaculture has a long history elsewhere, especially in China, where at least 50 species are grown, including finfish, shrimp, crab, other shellfish, sea turtles, and sea cucumbers (not a vegetable but a marine animal).[14] In the Szechuan area of China, fish are farmed on more than 100,000 hectares (about 250,000 acres) of flooded rice fields. This is an ancient practice that can be traced back to a treatise on fish culture written by Fan Li in 475 B.C.[14] In China and other Asian countries, farmers often grow several species of fish in the same pond, exploiting their different ecological niches. Ponds developed mainly for carp, a bottom-feeding fish, also contain minnows, which feed at the surface on leaves added to the pond.

Aquaculture can be extremely productive on a per-area basis, in part because flowing water brings food from outside into the pond or enclosure. Although the area of Earth that can support freshwater aquaculture is small, we can expect this kind of aquaculture to increase and become a more important source of protein.

Sometimes fishponds use otherwise wasted resources, such as fertilized water from treated sewage. Other fishponds exist in natural hot springs (Idaho) or use water warmed by being used to cool electric power plants (Long Island, New York; Great Britain).[14]

Mariculture, the farming of ocean fish, though producing a small part of the total marine fish catch, has grown rapidly in the last decades and will likely continue to do so. Oysters and mussels are grown on rafts lowered into the ocean, a common practice in the Atlantic Ocean in Portugal and in the Mediterranean in such nations as France. These animals are filter feeders—they obtain food from water that moves past them. Because a small raft is exposed to a large volume of water, and thus a large volume of food, rafts can be extremely productive. Mussels grown on rafts in bays of Galicia, Spain, produce 300 metric tons per hectare, whereas public harvesting grounds of wild shellfish in the United States yield only about 10 kg/ha (that's just a hundredth of a metric ton).[14] Oysters and mussels are grown on artificial pilings in the intertidal zone in the state of Washington (Figure 11.21).

FIGURE 11.21 **An oyster farm in Poulsbo, Washington.** Oysters are grown on artificial pilings in the intertidal zone.

Some Negatives

Although aquaculture has many benefits and holds great promise for our food supply, it also causes environmental problems. Fishponds and marine fish kept in shallow enclosures connected to the ocean release wastes from the fish and chemicals such as pesticides, polluting local environments. In some situations, aquaculture can damage biological diversity. This is a concern with salmon aquaculture in the Pacific Northwest, where genetic strains not native to a stream are grown and some are able to mix with wild populations and breed. Problems with salmon aquaculture demonstrate the need for improved methods and greater care about environmental effects.

CRITICAL THINKING ISSUE

Will There Be Enough Water to Produce Food for a Growing Population?

Between 2000 and 2025, scientists estimate, the world population will increase from 6.6 billion to 7.8 billion, approximately double what it was in 1974. To keep pace with the growing population, the United Nations Food and Agriculture Organization predicts, that food production will have to double by 2025, and so will the amount of water consumed by food crops. Will the supply of freshwater be able to meet this increased demand, or will the water supply limit global food production?

Growing crops consume water through transpiration (loss of water from leaves as part of the photosynthetic process) and evaporation from plant and soil surfaces. The volume of water consumed by crops worldwide—including rainwater and irrigated water—is estimated at 3,200 billion m^3 per year. An almost equal amount of water is used by other plants in and near agricultural fields. Thus, it takes 7,500 billion m^3 per year of water to supply crop ecosystems around the world (see Table 11.2). Grazing and pastureland account for another 5,800 billion m^3, and evaporation from irrigated water another 500 billion m^3, for a total of 13,800 billion m^3 of water per year for food production, or 20% of the water evaporated and transpired worldwide. By 2025, therefore, humans will be appropriating almost half of all the water available to life on land for growing food for their own use. Where will the additional water come from?

Table 11.2 ESTIMATED WATER REQUIREMENTS OF FOOD AND FORAGE CROPS

CROP	LITERS/KG
Potatoes	500
Wheat	900
Alfalfa	900
Sorghum	1,110
Corn	1,400
Rice	1,912
Soybeans	2,000
Broiler chicken	3,500*
Beef	100,000*

* Includes water used to raise feed and forage.

Source: D. Pimentel et al., "Water Resources: Agriculture, the Environment, and Society," *Bioscience* 4, no. 2 [February 1997]: 100.

Although the amount of rainwater cannot be increased, it can be used more efficiently through farming methods such as terracing, mulching, and contouring. Forty percent of the global food harvest now comes from irrigated land, and some scientists estimate that the volume of irrigation water available to crops will have to triple by 2025—to a volume equaling 24 Nile rivers or 110 Colorado rivers.[26] A significant saving of water can therefore come from more efficient irrigation methods, such as improved sprinkler systems, drip irrigation, night irrigation, and surge flow.

Surge flow is the intermittent application of water along furrows—on and off periods of water flow at constant or variable intervals. Often, this can completely irrigate a crop in much less time and therefore wastes much less water than does constant irrigation, which allows much more time for water to evaporate. Surge flow is also useful for young plants, which need only a small amount of water.

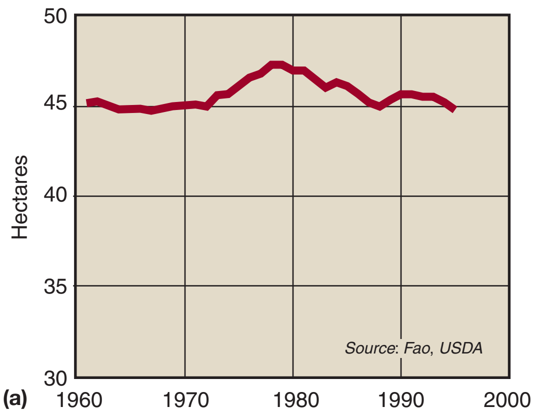
Additional water could be diverted from other uses to irrigation, but this might not be as easy as it sounds because of competing needs for water. For example, if water were provided to the 1 billion people in the world who currently lack drinking and household water, less would be available for growing crops. And the new billions of people to be added to the world population in the next decades will also need water. People already use 54% of the world's runoff. Increasing this to more than 70%, as will be required to feed the growing population, may result in a loss of freshwater ecosystems, decline in world fisheries, and extinction of aquatic species.

In many places, groundwater and aquifers are being used faster than they are being replaced—a process that is unsustainable in the long run. Many rivers are already so heavily used that they release little or no water to the ocean. These include the Ganges and most other rivers in India, the Huang He (Yellow River) in China, the Chao Phraya in Thailand, the Amu Darya and Syr Darya in the Aral Sea basin, and the Nile and Colorado rivers.

Two hundred years ago, Thomas Malthus put forth the proposition that population grows more rapidly than the ability of the soil to grow food and that at some time the human population will outstrip the food supply. Malthus might be surprised to know that by applying science and technology to agriculture, food production has so far kept pace with population growth. For example, between 1950 and 1995, the world population increased 122% while grain productivity increased 141%. Since 1995, however, grain production has slowed down (see Figure 11.22), and the question remains whether Malthus will be proved right in the 21st century. Will science and technology be able to solve the problem of water supply for growing food for people, or will water prove a limiting factor in agricultural production?

Critical Thinking Questions

1. How might dietary changes in developed countries affect water availability?
2. How might global warming affect estimates of the amount of water needed to grow crops in the 21st century?
3. Withdrawing water from aquifers faster than the replacement rate is sometimes referred to as "mining water." Why do you think this term is used?
4. Many countries in warm areas of the world are unable to raise enough food, such as wheat, to supply their populations. Consequently, they import wheat and other grains. How is this equivalent to importing water?
5. Malthusians are those who believe that sooner or later, unless population growth is checked, there will not be enough food for the world's people. Anti-Malthusians believe that technology will save the human race from a Malthusian fate. Analyze the issue of water supply for agriculture from both points of view.



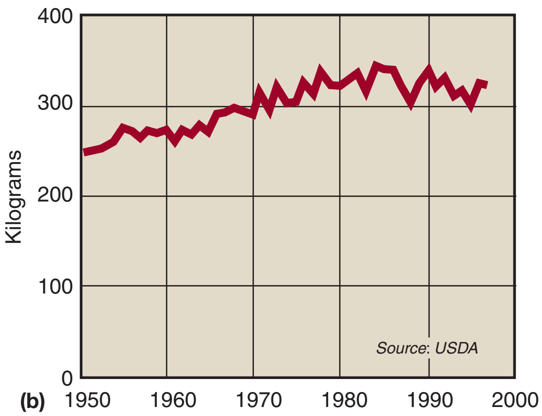


FIGURE 11.22 **(a) World irrigated area per thousand people, 1961–95.** (*Source*: L.R. Brown, M. Renner, and C. Flavin, *Vital Signs: 1998* [New York: Norton, 1998], p. 47.) **(b)** World grain production per person, 1950–1977. (*Source*: Brown, Renner, and Flavin, *Vital Signs*, p. 29.)

SUMMARY

- Agriculture changes the environment; the more intense the agriculture, the greater the changes.
- From an ecological perspective, agriculture is an attempt to keep an ecosystem in an early-successional stage.
- Farming greatly simplifies ecosystems, creating short and simple food chains, growing a single species or genetic strain in regular rows in large areas, reducing species diversity and reducing the organic content and overall fertility of soils.
- These simplifications open farmed land to predators and parasites, increased soil loss, erosion, and, thus, downstream sedimentation, and increased pollution of soil and water with pesticides, fertilizers, and heavy metals concentrated by irrigation.
- The history of agriculture can be viewed as a series of attempts to overcome environmental limitations and problems. Each new solution has created new environmental problems, which have in turn required their own solutions.
- The Industrial Revolution and the rise of agricultural sciences have revolutionized agriculture in two areas—one ecological and the other genetic—with many benefits and some serious drawbacks.
- Modern fertilizers, irrigation methods, and hybridization have greatly increased the yield per unit area. Modern chemistry has led to the development of a wide variety of pesticides that have reduced, though not eliminated, the loss of crops to weeds, diseases, and herbivores, but these have also had undesirable environmental effects. In the future, pest control will be dominated by integrated pest management.

- Most 20th-century agriculture has relied on machinery and the use of abundant energy, with relatively little attention paid to the loss of soils, the limits of groundwater, and the negative effects of chemical pesticides.
- Overgrazing has severely damaged lands. It is important to properly manage livestock, including using appropriate lands for grazing and keeping livestock at a sustainable density.

REEXAMINING THEMES AND ISSUES

Human Population

Agriculture is the world's oldest and largest industry; more than one-half of all the people in the world still live on farms. Because the production, processing, and distribution of food alter the environment, and because of the size of the industry, large effects on the environment are unavoidable.

Sustainability

Alternative agricultural methods appear to offer the greatest hope of sustaining agricultural ecosystems and habitats over the long term, but more tests and better methods are needed. As the experience with European agriculture shows, crops can be produced on the same lands for thousands of years as long as sufficient fertilizers and water are available; however, the soils and other aspects of the original ecosystem are greatly changed—these are not sustained. In agriculture, production can be sustained, but the ecosystem may not be.

Global Perspective

Agriculture has numerous global effects. It changes land cover, affecting climate at regional and global levels, increasing carbon dioxide in the atmosphere, and adding to the buildup of greenhouse gases, which in turn affects climate. Fires to clear land for agriculture may significantly affect the climate by adding small particulates to the atmosphere. Genetic modification is a new global issue that has not only environmental but also political and social effects.

Urban World

The agricultural revolution makes it possible for fewer and fewer people to produce more and more food and leads to greater productivity per acre. Freed from dependence on farming, people flock to cities, which leads to increased urban effects on the land. Thus, agricultural effects on the environment indirectly extend to the cities.

People and Nature

Farming is one of the most direct and large-scale ways that people affect nature. Our own sustainability, as well as the quality of our lives, depends heavily on how we farm.

Science and Values

Human activities have seriously damaged one-fourth of the world's total land area, impacting one-sixth of the world's population (about 1 billion people). Overgrazing, deforestation, and destructive farming practices have caused so much damage that recovery in some areas will be difficult, and restoration of the rest will require serious actions. A major value judgment we must make in the future is whether our societies will allocate funds to restore these damaged lands. Restoration requires scientific knowledge, both about present conditions and about actions required for restoration. Will we seek this knowledge and pay for it?

KEY TERMS

agroecosystem **213**
aquaculture **230**
biological control **226**
genetically modified crops **229**
green revolution **228**
integrated pest management **226**
Liebig's law of the minimum **223**
limiting factor **223**
macronutrient **223**
malnourishment **216**
mariculture **230**
micronutrient **223**
monoculture **214**
organic farming **228**
pasture **218**
rangeland **218**
synergistic effect **224**
terminator gene **229**
undernourishment **216**

STUDY QUESTIONS

1. Design an integrated pest management scheme for a small vegetable garden in a city lot behind a house. How would this scheme differ from integrated pest management used on a large farm? What aspects of IPM could not be used? How might the artificial structures of a city be put to use to benefit IPM?

2. Under what conditions might grazing cattle be sustainable when growing wheat is not? Under what conditions might a herd of bison provide a sustainable supply of meat when cows might not?

4. Pick one of the nations in Africa that has a major food shortage. Design a program to increase its food production. Discuss how reliable that program might be given the uncertainties that nation faces.

5. Should genetically modified crops be considered acceptable for "organic" farming?

6. You are about to buy your mother a bouquet of 12 roses for Mother's Day, but you discover that the roses were genetically modified to give them a more brilliant color and to produce a natural pesticide through genetic energy. Do you buy the flowers? Explain and justify your answer based on the material presented in this chapter.

7. A city garbage dump is filled, and it is suggested that the area be turned into a farm. What factors in the dump might make it a good area to farm, and what might make it a poor area to farm?

8. You are sent into the Amazon rain forest to look for new crop species. In what kinds of habitats would you look? What kinds of plants would you look for?

FURTHER READING

Borgstrom, G., ***The Hungry Planet: The Modern World at the Edge of Famine*** (New York: Macmillan, 1965). A classic book by one of the leaders of agricultural change.

Cunfer, G., ***On the Great Plains: Agriculture and Environment*** (College Station: Texas A&M University Press, 2005). Uses the history of European agriculture applied to the American Great Plains as a way to discuss the interaction between nature and farming.

Manning, R., ***Against the Grain: How Agriculture Has Hijacked Civilization*** (New York: North Point Press, 2004). An important iconoclastic book in which the author attributes many of civilization's ills—from war to the spread of disease—to the development and use of agriculture. In doing so, he discusses many of the major modern agricultural issues.

Mazoyer, Marcel, and Laurence Roudar, ***A History of World Agriculture: From the Neolithic Age to the Current Crisis*** (New York: Monthly Review Press, 2006). By two French professors of agriculture, this book argues that the world is about to reach a new farming crisis, which can be understood from the history of agriculture.

McNeely, J.A., and S.J. Scherr, ***Ecoagriculture*** (Washington, DC: Island Press, 2003). Smil, V., *Feeding the World* (Cambridge, MA: MIT Press, 2000).

Seymour, John, and Deirdre Headon, eds., ***The Self-sufficient Life and How to Live It*** (Cambridge: DK ADULT, 2003). Ever think about becoming a farmer and leading an independent life? This book tells you how to do it. It is an interesting, alternative way to learn about agriculture. The book is written for a British climate, but the messages can be applied generally.

Terrence, J. Toy, George R. Foster, and Kenneth G. Renard, ***Soil Erosion: Processes, Prediction, Measurement, and Control*** (New York: John Wiley, 2002).