A Farm Where Animals Do Most of the Work

It is common for a farmer growing juicy tomatoes or sweet apples to become a local hero, but how often does a farmer become known throughout an entire country?

Joel Salatin of Swoope, Virginia, has been featured in a best-selling book and two major motion pictures. He is the author of numerous popular books, including Holy Cows and Hog Heaven: The Food Buyer’s Guide to

Salatin understands that farming, done properly, has to replicate many of the processes that exist in nature.
Farm Friendly Food and Everything I Want to Do Is Illegal: War Stories From The Local Food Front. His farming has drawn the attention of authors, filmmakers, and tens of thousands of other people because he raises vegetables and livestock in a sustainable, organic way. Salatin understands that farming, done properly, has to replicate many of the processes that exist in nature.

Salatin told author Michael Pollan that he is a “grass farmer.” Salatin understands that grass is at the foundation of the trophic pyramid. On his Polyface Farm, he grows grass that is harvested, dried by the Sun, and turned into hay, which he feeds to cattle. The cattle are processed into beef and consumed by humans. But that is only one piece of the intricate food chain that Salatin has created on his farm—all without chemical pesticides or synthetic fertilizers.

The “sanitation crew” cleans up after the cattle.

As cattle graze a field, they leave behind large piles of manure. After a few days, these piles of manure become the energy source for large numbers of grubs and fly larvae. Before the larvae can hatch and produce a fly problem on the farm, however, Salatin brings in his “sanitation crew”—not people spraying pesticides, but chickens, which eat the larvae and, in the process, spread the nitrogen-rich cow manure and deposit some of their own. Throughout this process, the chickens continue to lay eggs, which are tasty and nutritious. In nature, Salatin says, birds follow herbivores to take advantage of their waste, so that’s what he does on his farm.

Salatin uses other animals to take care of a different manure problem: the buildup of cow manure during winter, when his cattle are kept in a barn. Some farmers push that manure out the doorway and end up with huge manure piles in the spring. Salatin has a different approach. He layers straw (dried stalks of plants—in essence, another type of grass) and wood chips (from another producer, trees) on top of the manure and allows the floor of his barn to rise higher and higher during winter.
Occasionally he throws down some corn. During the winter, the manure-straw-corn layer decomposes and produces heat, which allows the cattle to use less energy and food to stay warm. In spring, when the cattle go out to pasture, he brings pigs into the barn. Pigs have an excellent sense of smell, and they dig up soil—or in this case, layers of manure and straw—with their snouts. One of their favorite foods is corn, and they find fermented corn that has been layered in a manure pile especially delectable. Within a few weeks, the pigs provide Salatin with a barn full of thoroughly mixed compost that required no machinery to make: his animals have done the work for him while they gained nutrients and calories.

These are just two examples of the way one farmer uses natural processes and knowledge of plants, animals, and the natural world to grow food for human consumption. Most agricultural methods, especially the modern ones practiced in the developed countries of the world, tend to fight the basic laws of ecology to provide large amounts of food for humans. These modern methods also use large amounts of fossil fuel in every step of the process, from the use of machinery in plowing and harvesting crops to the production of fertilizers and pesticides to the transportation and processing of the food. In contrast, Joel Salatin and other farmers interested in sustainable farming are finding ways to feed the human population by working with, not against, the natural world.


---

**KEY IDEAS**

A rapidly growing human population needs increasing amounts of food to sustain it. Since agriculture was first practiced more than 10,000 years ago, farmers have been able to increase the world’s agricultural output with improved technology and more efficient use of resources. Today, improvements in food production are also being realized through direct manipulation of genetic material in crops. While these improvements have been beneficial to humanity, they also have environmental costs.

After reading this chapter you should be able to

- describe human nutritional needs and the challenges of overcoming hunger and malnutrition.
- explain the development of modern industrial agriculture, the role played by inputs such as irrigation water, fertilizers, and pesticides, and the environmental consequences of modern farming methods.
- identify the benefits and costs of using genetically modified organisms in agriculture.
- describe alternatives to industrial farming methods.
- explain the environmental impacts of various approaches to raising and harvesting meat and fish.
11.1 Human nutritional requirements are not always satisfied

Humans survived by hunting and gathering until 10,000 years ago—plus or minus a few thousand years—when agriculture began. Before that time, our ancestors were subject to natural and human-caused variations in the abundance of wild animals and plants. Starvation was common, and, in times of scarcity, very few people received an adequate diet. Advancements in agricultural methods have greatly improved the human diet over the last 10,000 years. In particular, tremendous gains in agricultural productivity and food distribution were made in the 20th century. But despite these advances, many people throughout the world still do not get adequate nutrition. As many as 24,000 people starve to death each day—8.8 million people each year.

As FIGURE 11.1 shows, about 1 billion people worldwide lack access to adequate amounts of food. That number had been declining for decades, but has been increasing again since 1996. The recent increase is due in part to a decrease in government assistance for agricultural development in much of the developing world over the last 15 years. More recently, it has been made worse by an increase in fuel prices and the global economic downturn.

In this section we will look at basic human nutritional needs, how those needs are met, and the reasons why they are not always met. In the following sections we will discuss various agricultural methods and their environmental implications.
11.1.1 NUTRITIONAL REQUIREMENTS

Chronic hunger, or undernutrition, means not consuming enough calories to be healthy. Food calories are converted into usable energy by the human body. Not receiving enough food calories leads to an energy deficit. An average person needs approximately 2,200 kilocalories per day, though this amount varies with gender, age, and weight. A long-term food deficit of only 100 to 400 kilocalories per day—in other words, an intake of 100 to 400 kilocalories less than one’s daily need—deprives a person of the energy needed to perform daily activities and makes the person more susceptible to disease. In children, undernutrition can lead to improper brain development and lower IQ.

In addition, a person lacking sufficient food calories is probably lacking sufficient protein and other nutrients. According to the World Health Organization (WHO), 3 billion people—nearly one-half of the world’s population—are malnourished; that is, regardless of the number of calories they consume, their diets lack the correct balance of proteins, carbohydrates, vitamins, and minerals, and they experience malnutrition.

The Food and Agriculture Organization of the United Nations (FAO) defines food security as the condition in which people have access to sufficient, safe, and nutritious food that meets their dietary needs for an active and healthy life. Access refers to the economic, social, and physical availability of food. Food insecurity refers to the condition in which people do not have adequate access to food.

Famine is a condition in which food insecurity is so extreme that large numbers of deaths occur in a given area over a relatively short period. Actual definitions of famine vary widely depending on the agency using the term. One relief agency defines a famine as an event in which there are more than 5 deaths per day per 10,000 people due to lack of food. According to this definition, there is an annual mortality rate of 18 percent during a famine. Famines are often the result of crop failures, sometimes due to drought, although famines can have social and political causes as well.

Even when people have access to sufficient food, a deficit in just one essential vitamin or mineral can have drastic consequences. The WHO estimates that more than 250,000 children per year become blind due to a vitamin A deficiency. Iron deficiency, known as anemia, is the most widespread nutritional deficiency in the world. The WHO estimates that there are 3 billion anemic people in the world—many in developing countries, but also in developed countries. Lack of dietary iron is the major cause of anemia, but there are other causes, including malaria, AIDS, and parasite infestations. An increase in the ingestion of iron-rich foods, such as certain grains, herbs, vegetables, and meats, can reduce anemia.

Figure 11.2 Annual meat consumption. Per capita meat consumption has increased, both globally and in the United States. [After http://earhtrends.wri.org.]
In the last few decades, one other form of malnutrition has been increasing. Overnutrition, the ingestion of too many calories and improper foods, causes a person to become overweight. The WHO estimates that there are over 1 billion people in the world who are overweight, and that roughly 300 million of those people are obese, meaning they are more than 20 percent above their ideal weight. Overnutrition is a type of malnutrition that puts people at risk for a variety of diseases, including Type 2 diabetes, hypertension, heart disease, and stroke. While overnutrition is common in developed countries such as the United States, it can also coexist with malnutrition in developing countries. Childhood obesity is a related condition that has started to occur in greater numbers. Overnutrition is often a function of the availability and affordability of certain kinds of foods. For example, overnutrition in the United States has been attributed in part to the easy availability and low cost of processed foods containing ingredients such as high-fructose corn syrup, which are often high in calories and lacking in other nutritional content.

Humans eat a variety of foods, but grains—the seedlike fruits of corn (maize), rice, wheat, and rye, among others—make up the largest component of the human diet. Worldwide, there are roughly 50,000 edible plant species, but just three of them—corn, rice, and wheat—constitute 60 percent of human energy intake. Globally, we produce over 300 kg (660 pounds) of grain per person per year, followed by meat at 40 kg (88 pounds) per person per year, and fish at about 21 kg (46 pounds) per person per year. Meat, the second largest component of the human diet, is usually defined as livestock (beef, veal, pork, and lamb) and poultry (chicken, turkey, and duck). As income increases with economic growth, people tend to add more meat to their diet. As FIGURE 11.2 shows, meat consumption has been increasing both globally and in the United States.
11.1.2 REASONS FOR UNDERNUTRITION AND MALNUTRITION

Currently, the world’s farmers grow enough grain to feed at least 8 billion people, which would appear to be more than enough for the world’s population of 6.8 billion. And grain is only a little more than one-half of the food we produce, in terms of calorie content or biomass. Why, then, are undernutrition and malnutrition common in so many countries of the world? There are many ways to examine this question, and the answers are equally complex.

The primary reason for undernutrition and malnutrition is poverty: the lack of resources that allow one access to food. According to many food experts, starvation on a global scale is the result of unequal food distribution rather than absolute food scarcity. In other words, the food exists, but not everyone has access to it. This may mean that people cannot afford to buy the food they need, which is a problem that cannot be solved just by producing more grain.

In addition, political and economic factors play an important role. For example, refugee populations that have fled their homes due to war or natural disasters do not have access to food that they may have grown and stored, but left behind when they became refugees. Lack of an adequate food supply has led to political unrest many times in modern history. People without the means to feed themselves or their families are likely to resort to crime or violence in an attempt to improve their situation. Most recently, a rise in food prices in 2008 led to food riots in Haiti, Egypt, Ivory Coast, Cameroon, Yemen, and elsewhere. Poor governance and political unrest can lead to inadequate food supplies as well, so they can be both causes and effects of undernutrition and malnutrition.

Food researchers have also observed that large amounts of agricultural resources are diverted to feed livestock and poultry rather than people. In fact, roughly 40 percent of the grain grown in the world is used to feed livestock. In the United States, the two largest agricultural crops, corn and soybeans, are grown primarily as animal feed. When these foods are fed to livestock, the low efficiency of energy transfer causes much of the energy they contain to be lost from the system, as we saw in Chapter 3. Ultimately, perhaps only 10 to 15 percent of the calories in grain or soybeans fed to cattle are converted into calories in beef. If people ate producers, such as grains and soybeans, rather than primary consumers, such as cattle, it is possible that more food would be available for people.

Figure 11.3 Global grain production, 1950–2006. (a) Global grain production grew rapidly from 1950 through the mid-1980s. Growth has continued since then, but it has slowed. (b) Global per capita grain production has leveled off and may be starting to decline. [After http://earthtrends.wri.org.]
FIGURE 11.3 shows global grain production since 1950. A large number of factors influence grain production, including the amount of land under cultivation, global weather and precipitation patterns, world prices for grain, and the productivity of the land on which grain is being grown. As FIGURE 11.3a shows, grain production has been steadily increasing, though there have been some years within the last decade with no increase. Per capita grain production, however, has been level since 1980 and may actually be declining. No one knows exactly why global per capita grain production has not continued to increase. Some environmental scientists suggest that we have finally reached the limit of our ability to supply the human population with food. Others blame some of the political and social factors mentioned above.

In Chapter 7 we learned that the human population is expected to be close to 9 billion, or even larger, by 2050. To feed everyone in the future, we will have to put more land into agricultural production, improve crop yields, reduce consumption of meat, harvest more from the world’s fisheries, or use some combination of these strategies.

Experts disagree on whether it is feasible to greatly expand food production. Optimists point to new techniques for crop development as well as unused land in tropical rainforests and grasslands, while pessimists argue that climate change, decreasing biodiversity, dwindling supplies of water for irrigation, diminishing topsoil, and other factors may make it difficult to produce more crops. To understand what we can do to improve food security in all nations of the world and reduce the environmental consequences of growing food, we will need to examine the farming methods we use today and the trade-offs involved in using those methods.

CHECKPOINT

• What are undernutrition and malnutrition?

• What is food insecurity?

• What are some of the possible reasons for food insecurity in the world today?
11.2 The Green Revolution and industrial farming methods have transformed agriculture

Roughly 10,000 years ago, people began to domesticate and raise animals, cultivate the soil, and domesticate, or modify by selective breeding, certain wild plant species to turn them into crops. The advent of agriculture was a major event in human history because it enabled people to move beyond a subsistence level of existence. At the same time, it has had some negative consequences.

The abundance of food supplied by agriculture is one factor that has led to the exponential growth of the human population, as we saw in Chapter 7. Deliberate cultivation of food also initiated a level of environmental degradation never before experienced on Earth. Some people speak of agriculture collectively as “the single most harmful human action that has taken place.” While this may be an overstatement, it is true that an increase in food production leads to a positive feedback loop: with more food come more people, who require even more food production.

In the twentieth century, farming became more mechanized, and the use of fossil fuel energy increased. These changes have led to increasing food output as well as a variety of environmental impacts. Industrial agriculture, or agribusiness, applies the techniques of the Industrial Revolution—mechanization and standardization—to the production of food. Today’s modern agribusinesses are quite different from the small family farms that dominated agriculture a few decades ago. We will begin this section by considering the ways in which modern industrial agriculture is dependent on energy, then describe the activities those additional energy inputs allow.
11.2.1 THE ENERGY SUBSIDY IN AGRICULTURE

Figure 11.4 Energy subsidies for various methods of food production and diets. Energy input per calorie of food obtained is greater for modern agricultural practices than for traditional agriculture. Energy inputs for hunting and gathering and for small-scale food production are mostly in the form of human energy, whereas fossil fuel energy is the primary energy subsidy for large-scale modern food production. All values are approximate, and for any given method there is a large range of values.
A great deal of energy, in addition to solar energy, goes into growing, harvesting, processing, and preparing food. These energy inputs include both fossil fuel energy and human energy. The energy input per calorie of food produced is called the energy subsidy. In other words, if we use 5 calories of energy to produce food, and we receive 1 calorie of energy when we eat that food, then the food has an energy subsidy of 5. We can think of this in another way if we use mass of inputs and outputs as a substitute measure for energy. It may take 20 kg (44 pounds) of grain to feed to cattle to produce 1 kg (2.2 pounds) of beef (an energy subsidy of 20). It takes only 2.8 kg (6 pounds) of grain to feed to chickens to produce 1 kg (2.2 pounds) of chicken meat (an energy subsidy of 2.8). This analogy is not perfect, because the energy content of 1 kg of beef is greater than that of 1 kg of grain. Nevertheless, it should help you understand the relationship between inputs and outputs in producing food. There are other considerations related to producing food, such as how much land is needed. This concept was part of the ecological footprint described in Chapter 1. Do the Math “Land Needed for Food” shows you how to calculate the different land requirements for obtaining sufficient calories from corn and from beef.

As FIGURE 11.4 shows, traditional small-scale agriculture requires a relatively small energy subsidy: it uses few energy inputs per calorie of food produced. By contrast, food writer Michael Pollan estimates that if you eat the average modern U.S. diet obtained from a typical supermarket, containing primarily foods produced by modern agricultural methods, there is a 10-calorie energy input for every calorie you eat. As this difference shows, food choices are energy choices.
DO THE MATH

Land Needed for Food

We have seen that raising beef requires more resources than growing corn. Let's look at some of the actual numbers.

On farms in the midwestern United States, a hectare of land yields roughly 370 bushels of corn (equivalent to 150 bushels per acre). A bushel consists of 1,250 ears of corn, and each ear typically contains 80 kilocalories. Assume that a person eats only corn and requires 2,000 kilocalories per day. Although this assumption is not very realistic, it allows an approximation of how much land it would take to feed that person.

The person's food requirement is

\[ 2,000 \text{ kilocalories/day} \times 365 \text{ days/year} = 730,000 \text{ kilocalories/year} \]

A hectare of corn produces

\[ 370 \text{ bushels/hectare} \times 1,250 \text{ ears/bushel} \times 80 \text{ kilocalories/ear} = 37,000,000 \text{ kilocalories/hectare} \]

Thus, one person eating only corn can obtain sufficient calories from 0.02 ha (0.05 acres) of land.

What if that person ate only beef? We have seen that it takes 20 kg of grain to produce 1 kg of beef. So it would take 20 times as much land, or 0.4 ha (1 acre), to feed a person who ate only beef.

What happens if we extend this analysis to a global scale? If Earth has about 1.5 billion hectares (3.7 billion acres) of land suitable for growing food, is there sufficient land on Earth to feed all 6.8 billion inhabitants of the planet if they all ate a diet of only beef?

\[ 6.8 \text{ billion people} \times 0.4 \text{ ha/person} = 2,720,000,000 \text{ ha} \]

So 2.72 billion hectares (6.72 billion acres) would be needed, and the answer is no.

Your Turn: How many people eating a beef-only diet could Earth support?
Most of the energy subsidies in modern agriculture are in the form of fossil fuels, which are used to produce fertilizers and pesticides, to operate tractors, to pump water for irrigation, and to harvest food and prepare it for transport. Other energy subsidies take place off the farm. For example, the average food item travels 2,000 km (1,240 miles) from the farm to your plate, so we often spend far more energy on transporting food than we get from the food itself. The Department of Energy reports that in the United States, 17 percent of total commercial energy use goes into growing, processing, transporting, and cooking food. Those of us eating a “supermarket” diet in the developed world are highly dependent on fossil fuel for our food; the modern agricultural system would not work without it.

How did we get to this point? In the twentieth century, the agricultural system was dramatically transformed from a system of small farms relying mainly on human labor and with relatively low fossil fuel inputs to a system of large industrial operations with fewer people and much more machinery. This shift in farming methods, known as the Green Revolution, involved new management techniques and mechanization as well as the triad of fertilization, irrigation, and improved crop varieties. These changes increased food production dramatically, and farmers were able to feed many more people.

The Green Revolution began with the work of crop scientists, particularly the American scientist Norman Borlaug (1914−2009), who won the Nobel Peace Prize for his contribution to increasing the world food supply. Through intensive breeding, Borlaug and other agricultural researchers developed new strains of wheat that produced higher yields and were disease resistant. They also used fertilizers and irrigation to improve yields. In the 1940s, researchers brought these techniques to developing nations such as Mexico and the Philippines to help them increase their agricultural output to feed their growing populations. From the 1950s through the 1970s, many countries, particularly those in the developing world, underwent similar shifts in the way they farmed.

The upward trend in world grain production that can be seen in FIGURE 11.3a is the result of the Green Revolution. From the mid-1960s through the mid-1980s, world grain production doubled. By the 1990s, there were at least 18 organizations around the world promoting and developing Green Revolution techniques, including mechanization, irrigation, use of fertilizer, monocropping, and use of pesticides. However, the Green Revolution has also had negative environmental impacts. Let’s examine some Green Revolution practices in more detail.

**MECHANIZATION** Farming involves many kinds of work. Fields must be plowed, planted, irrigated, weeded, protected from pests, harvested, and prepared for the next season. Even after harvesting, crops must be dried, sorted, cleaned, and prepared for market in almost as many different ways as there are different crops. Machines do not necessarily do this work better than humans or animals, but it can be economically advantageous to replace humans or animals with
machinery, particularly if fossil fuels are abundant, fuel prices are relatively low, and labor prices are relatively high. In developed countries, where wages are relatively high, less than 5 percent of the workforce works in agriculture. In developing countries, where wages tend to be much lower, 40 to 75 percent of the working population is employed in agriculture.

Since the advent of mechanization, large farms producing staple crops such as beans or corn have generally been more profitable than small farms. The reason for this is economies of scale, by which we mean that the average costs of production fall as the output increases. For example, a new combine harvester—a machine that harvests the crop and separates out the grain or seed for transport—costs between $150,000 and $400,000. This large up-front expenditure is a good investment for a large farm, where the cost of the machine is justified by the profits on the increased production that comes from using it. A small farm, however, does not have enough land to be able to recoup the cost of such expensive equipment. Because of economies of scale, profits tend to increase with size, and large agricultural operations generally outcompete small ones. As a result, between 1950 and 2000, the average farm size in Iowa more than doubled, from about 70 ha (173 acres) to over 140 ha (346 acres).

Mechanization also means that single-crop farms are generally more efficient than farms that grow many crops. Mechanized crop planting and picking require specialized, expensive equipment that is specific to each crop, so planting and harvesting only a single type of crop reduces equipment costs.

**Figure 11.5 Irrigation circles.** The green circles in this aerial photograph from Oregon are obvious evidence of irrigation.

**IRRIGATION** Irrigation systems like those described in Chapter 9 can increase crop growth rates or even enable crops to grow where they could not otherwise be grown (FIGURE 11.5). For example, irrigation has transformed approximately 400,000 ha (1 million acres) of former desert in the Imperial Valley of southeastern California into a major producer of fruits.
and vegetables. In other situations, irrigation can allow productive land to become extremely productive land. One estimate suggests that, whereas 16 percent of the world’s agricultural land is irrigated, that land produces 40 percent of the world’s food.

While irrigation has many benefits, including more efficient use of water in some places where it is scarce, it can have a number of negative consequences over time. It can deplete groundwater and draw down aquifers, as we saw in the case of the Ogallala aquifer in Chapter 9. In coastal areas, it can promote saltwater intrusion into freshwater wells. It can also contribute to soil degradation through waterlogging and salinization. Waterlogging, which occurs when soil remains under water for prolonged periods, impairs root growth because roots cannot get oxygen. Salinization occurs when the small amounts of salts in irrigation water become highly concentrated on the soil surface through evaporation. As FIGURE 11.6 illustrates, these salts can eventually reach toxic levels and impede plant growth.

**Figure 11.6**  
**Irrigation-induced salinization and waterlogging.**  
Over time, irrigation can degrade soil by leaving a layer of highly concentrated salts at the soil surface and waterlogged soil below.

**FERTILIZERS**  
Agriculture removes organic matter and nutrients from soil, and if these materials are not replenished, they can be quickly depleted. Because industrial agriculture keeps soil in constant production, it
requires large amounts of fertilizers to replace lost organic matter and nutrients. Fertilizers contain essential nutrients for plants—primarily nitrogen, phosphorus, and potassium—and they foster plant growth where one or more of these nutrients is lacking. There are two types of fertilizers used in agriculture: organic and synthetic.

As their name suggests, organic fertilizers are composed of organic matter from plants and animals. They are typically made up of animal manure that has been allowed to decompose. Traditional farmers often spread animal manure and crop wastes onto fields to return some of the nutrients that were removed from those fields when crops were harvested.

Synthetic, or inorganic, fertilizers are produced commercially. Nitrogen fertilizers are often produced by combusting natural gas, which allows nitrogen from the atmosphere to be fixed and captured in fertilizer. Fertilizers produced in this way are highly concentrated, and their widespread use has increased crop yields tremendously since the Green Revolution began. Synthetic fertilizers have many advantages over organic fertilizers. They are designed for easy application, their nutrient content can be targeted to the needs of a particular crop or soil, and plants can easily absorb them, even in poor soils. Worldwide, synthetic fertilizer use increased from 20 million metric tons in 1960 to 160 million metric tons in 2007. It is arguable that without synthetic fertilizers, we could not feed all the people in the world.

**Figure 11.7 Fertilizer runoff after fertilization.**
The proximity of this drainage ditch to an agricultural field may lead to runoff of fertilizer during a heavy rainstorm.

Despite these advantages, synthetic fertilizers can have several adverse effects on the environment. The process of manufacturing synthetic fertilizers uses fossil fuel energy. Producing nitrogen fertilizer is an especially energy-intensive process. Furthermore, whereas synthetic fertilizers are more readily available for plant uptake than organic fertilizers, they are also more likely to be carried by runoff into adjacent waterways and aquifers. In surface waters, this nutrient runoff can cause algae and other organisms to proliferate. After these organisms die, they decompose and reduce oxygen levels.
in the water, a process we will learn more about when we look at water pollution in Chapter 14. Finally, synthetic fertilizers do not add organic matter to the soil, as organic fertilizers do. As we saw in Chapter 8, organic matter contributes many beneficial properties to soil, including increased cation exchange capacity and water retention abilities.

In the United States, fertilizer use, and consequently nutrient runoff, is somewhat less than in other nations with similar agricultural output. Still, large amounts of nitrogen and other nutrients run into waterways in intensively farmed regions such as California’s Central Valley, farming regions along the East Coast, and the Mississippi River watershed (FIGURE 11.7).

**Figure 11.8 Monocropping.** This large field in Oregon contains only one crop species: soybeans. There are both advantages and disadvantages to monocropping.

MONOCROPPING Both the mechanization of agriculture and the use of synthetic fertilizers encourage large plantings of a single species or variety, a practice known as monocropping. Monocropping is the dominant agricultural practice in the United States, where wheat and cotton are frequently grown in monocrops of 405 hectares (1,000 acres) or more (FIGURE 11.8).

Monocropping has greatly improved agricultural productivity. This technique allows large expanses of land to be planted, and then harvested, all at the same time. With the use of large machinery, the harvest can be obtained easily and efficiently. If fertilizer or pesticide treatments are required, those treatments can also be applied uniformly over large fields, which, because they are planted with the same crop, have the same pesticide or nutritional needs.
Despite the benefits of increased efficiency and productivity, monocropping can lead to environmental degradation. First, soil erosion can become a problem. Because fields that are monocropped are readied for planting or harvesting all at once, soil will be exposed over many hectares at the same time. On a 405-hectare (1,000-acre) field that has not yet been planted, wind can blow for over 1.6 km (1 mile) without encountering anything but bare soil. Under these circumstances, the wind can gain enough speed to carry dry soil away from the field. Certain farmland in the United States loses an average of 1 metric ton of topsoil per hectare (2.5 metric tons per acre) per year to wind erosion. As we saw in Chapter 8, this topsoil contains important nutrients, and its loss can reduce productivity.

Monocropping also makes crops more vulnerable to attack by pests. Large expanses of a single plant species represent a vast food supply for any pests that specialize on that particular plant. Such pests will establish themselves in the monocrop and reproduce rapidly. Their populations may experience exponential growth similar to what we saw in Georgii Gause’s Paramecium populations supplied with unlimited food (see FIGURE 6.4). Natural predators may not be able to respond rapidly to the exploding pest population. Many predators of crop pests, such as ladybugs and parasitic wasps, are attracted to the pests that feed on monocrops. But these predators also rely on non-crop plants for habitat. Monocropping removes habitat for predators that might otherwise control the pest population.

PESTICIDES Because of the increased pest populations that monocropping encourages, as well as for other reasons, the use of pesticides has become routine and widespread in modern industrial agriculture. Pesticides are substances, either natural or synthetic, that kill or control organisms that people consider pests. In the United States, over 227 million kilograms (500 million pounds) of pesticides are applied to food crops, cotton, and fruit trees. The United States accounts for about one-third of worldwide pesticide use.

Insecticides target species of insects and other invertebrates that consume crops, and herbicides target plant species that compete with crops. Some pesticides are broad-spectrum pesticides, meaning that they kill many different types of pests, and some are selective pesticides that focus on a narrower range of organisms. The broad-spectrum insecticide dimethoate, for example, kills almost any insect or mite (mites are not insects, but rather relatives of ticks and spiders), while the more selective acequinocyl kills only mites.

The application of pesticides is a rapid, relatively easy response to an infestation of pests on an agricultural crop. In many cases, a single application can significantly reduce a pest population. By preventing crop damage, pesticides allow greater crop yields on less land, thereby reducing the area disturbed by agriculture. Thus the application of pesticides has made agriculture more efficient.
But pesticides, like other industrial agricultural practices, present some environmental problems. One of these problems is that pesticides injure or kill organisms other than their intended targets. Some pesticides, such as dichlorodiphenyltrichloroethane, also known as DDT, are persistent, meaning that they remain in the environment for a long time. In 1972, DDT was banned in the United States, in part because it was found to build up over time in the fatty tissues of predators through a process called bioaccumulation. DDT is a fat-soluble chemical that is not easily flushed from the body, but instead accumulates in fatty tissues. Whenever an organism containing the pesticide is eaten, the chemical is transferred to the consumer. This process eventually leads to very high pesticide concentrations at high trophic levels. Thus, even if pesticides are not concentrated enough to affect the organisms that initially consume them, they may affect organisms higher up the food chain, such as birds of prey and humans. Bioaccumulation is discussed further in Chapter 17.

Other pesticides, such as the herbicide glyphosate, known by the trade name Roundup, are nonpersistent, meaning that they break down relatively rapidly, usually in weeks to months. Nonpersistent pesticides have fewer long-term effects, but they must be applied more often, so their overall environmental impact is not always lower than that of persistent pesticides.

Another disadvantage of pesticide use is that pest populations may evolve resistance to pesticides over time, as described in Chapter 5. Pest populations are usually large and thus contain significant genetic diversity. In those vast gene pools, there are usually a few individuals that are not as susceptible to a pesticide as others, and those individuals may survive an initial application of the pesticide. Those surviving individuals are said to be resistant to the pesticide. If the pesticide is successful in reducing the pest population, then in the next generation, the fraction of resistant individuals in that population will increase. As time goes by, resistant individuals will make up a larger...
larger fraction of the population. Often the resistance becomes more effective as well, making the pesticide significantly less useful. At this point, crop scientists and farmers must search for a new pesticide. The cycle of pesticide development, followed by pest resistance, followed by new pesticide development, and so on—called the pesticide treadmill—is an example of a positive feedback system, as shown in FIGURE 11.9.

Figure 11.9  The pesticide treadmill. Over time, pest populations evolve resistance to pesticides, requiring farmers to use higher doses or to develop new pesticides.

Pesticides can cause even wider environmental effects. They may kill organisms that benefit farmers, such as predatory insects that eat crop pests, pollinator insects that pollinate crop plants, and plants that fix nitrogen and improve soil fertility. Furthermore, chemical pesticides, like fertilizers, can run off into surrounding surface waters and potentially enter groundwater, a problem we will look at in detail in Chapter 14. The toxicity of pesticides to farmworkers has been well documented. The risk to humans who ingest food that has been treated with pesticides is a subject of some debate and will be covered in Chapter 17.

CHECKPOINT

- Explain the energy subsidy in agriculture.
- What are the major features of the Green Revolution?
- What are the pros and cons of pesticide use?
11.3 Genetic engineering is revolutionizing agriculture

As we saw in Chapter 5, humans have modified plants and animals by artificial selection for thousands of years. Many crop species, for example, have been modified to increase their output of seeds or fruits. The modern techniques of genetic engineering, however, go far beyond these traditional practices. Scientists today can isolate a specific gene from one organism and transfer it into the genetic material of another, often very different, organism, producing a genetically modified organism, or GMO. By manipulating specific genes, agricultural scientists can rapidly produce organisms with desirable traits that may be impossible to develop by traditional breeding techniques.

11.3.1 THE BENEFITS OF GENETIC ENGINEERING

Genetically modified crops and livestock offer the possibility of greater yield and food quality, reductions in pesticide use, and higher profits for the agribusinesses that use them. They are also seen as a way to help reduce world hunger by increasing food production and reducing losses to pests and varying environmental conditions.

Figure 11.10 White rice and golden rice. (a) Crop scientists have inserted a gene that produces vitamin A into white rice. (b) The resulting genetically modified rice is called golden rice.
INCREASED CROP YIELD AND QUALITY Genetic engineering can increase food production in several ways. It can create strains of organisms that are resistant to pests and harsh environmental conditions such as drought or high salinity. In addition, agricultural scientists have begun to engineer plants to produce essential nutrients for humans. For example, agricultural scientists have inserted a gene for the production of vitamin A into rice plants, creating new seeds known as golden rice (FIGURE 11.10). Although golden rice is still an experimental product, some scientists hope that it will help reduce the incidence of blindness resulting from vitamin A deficiency. Crop plants, animals, and bacteria have also been modified to produce pharmaceuticals and other compounds, a process that can make these products far less expensive to produce. A number of projects are under way to create genetically modified animals for food production, including a salmon that grows to its full size of 3.6 kg (8 pounds) in 18 months—half the growing time of an unmodified fish.

POTENTIAL CHANGES IN PESTICIDE USE Genetic engineering for resistance to pests could reduce the need for pesticides. Corn, for example, is subject to attacks from the bollworm, European corn borer (Ostrinia nubilalis), and other lepidopteran (butterfly and moth) larvae. Bacillus thuringiensis is a natural soil bacterium that produces a toxin that can kill lepidopterans. The bacterium’s insecticidal gene, known as Bt, has been inserted into the genetic material of corn plants, resulting in a genetically modified plant that produces a natural insecticide in its leaves. By 2009, 63 percent of the land area planted with corn in the United States was planted with Bt corn. Growers of Bt corn have been able to reduce the amount of synthetic pesticide used on their corn crops.

A similar technique has been used to create crop plants that are resistant to the herbicide Roundup. The “Roundup Ready” gene allows growers to spray the herbicide on their fields to control the growth of weeds without harming the crop plants. It is now widely used in corn, soybean, and cotton plants. The success of no-till agriculture, which we will discuss later in this chapter, rests largely on the use of herbicides and the introduction of herbicide-resistant crops.

INCREASED PROFITS Because pesticides can be a significant expense on any farm, genetically modified crops have the potential to reduce expenses. In addition, because GMO crops often produce greater yields, there is also the potential for an increase in revenues. Both of these changes can lead to higher incomes for farmers, lower food prices for consumers, or both.

11.3.2 CONCERNS ABOUT GENETICALLY MODIFIED ORGANISMS

Industrial agriculture relies more heavily on genetically modified crops each year. In 2009, 63 percent of the corn, 91 percent of the soybeans, and 71 percent of the cotton planted in the United States came from genetically modified seeds. However, many European countries, as well as a number of people in the United States, question the safety of GMOs. Genetically modified crops and livestock are the source of considerable controversy. Concerns that have been raised include their safety for human consumption and their effects on biodiversity. Regulation of GMOs is also an issue, both in the United States and abroad.

SAFETY FOR HUMAN CONSUMPTION Some people are concerned that the ingestion of genetically modified foods may be harmful to humans, although so far there is little evidence to support these concerns. Researchers are studying the possibility that GMOs may cause allergic
reactions when people eat a food containing genes transferred from another food to which they are allergic.

**EFFECTS ON BIODIVERSITY** There is some concern that if genetically modified crop plants are able to breed with their wild relatives—as many domesticated crop plants are—the newly added genes will spread to the wild plants. The spread of such genes might then alter or eliminate natural plant varieties. Examples of GMOs crossing with wild relatives do exist. Because of these concerns, attempts have been made to introduce buffer zones around genetically modified crops.

The use of genetically modified seeds is contributing to a loss of genetic diversity among food crops. As with any reduction in biodiversity, we cannot know what beneficial genetic traits might be lost. For example, researchers recently discovered that one variety of sorghum, a cereal grass grown for its sweet juice extract, has a natural genetic variation that gives it resistance to a pest called the greenbug. This particular variety has since been used extensively to confer greenbug resistance on the U.S. sorghum crop. If growers had been growing only one or two genetically modified varieties of sorghum, this naturally resistant variety might have been eliminated before its beneficial trait was discovered.

**REGULATION OF GENETICALLY MODIFIED ORGANISMS** Currently, there are no regulations in the United States that mandate the labeling of genetically modified foods. Opponents of labeling argue that labeling of foods containing GMOs might suggest to consumers that there is something wrong with GMOs. They also argue that such labeling would be too difficult because small amounts of GMO materials are found throughout the U.S. agricultural system. Those who want to avoid consuming GMOs can safely purchase organic food; the federal definition of “organic” excludes genetically modified foods (see the Science Applied section that follows this chapter).

The U.S. government has not yet approved any genetically modified animals for market, but applications for a number of genetically modified animals are currently under consideration by the Food and Drug Administration.

**CHECKPOINT**

- What is a genetically modified organism?
- What are the major benefits of using GMOs?
- What are the disadvantages of using GMOs?
11.4 Alternatives to industrial farming methods are gaining more attention

Industrial agriculture has been so successful in reducing labor inputs, and has therefore become so widespread, that we generally call this type of farming conventional agriculture. However, in situations in which the cost of labor is not the most important consideration, traditional farming techniques may be economically successful as well. Small-scale farming is common in the developing world, where labor is less expensive than machinery and fossil fuels. In these countries, there are still many farmers growing crops on small plots of land. Traditional farming methods that differ from those of industrial agriculture include shifting agriculture and nomadic grazing, which are sometimes not sustainable, and more sustainable methods such as intercropping and agricultural forestry.

11.4.1 SHIFTING AGRICULTURE AND NOMADIC GRAZING

Locations with a moderately warm climate and relatively nutrient-poor soils, such as the rainforests of Central and South America, lend themselves to shifting agriculture. In these environments, a large fraction of the nutrients are contained within the vegetation. Shifting agriculture involves clearing land and using it for only a few years until the soil is depleted of nutrients. This traditional method of agriculture uses a technique sometimes called “slash-and-burn,” in which existing trees and vegetation are cut down, placed in piles, and burned (FIGURE 11.11). The resulting ash is rich in potassium, calcium, and magnesium, which makes the soil more fertile. However, these nutrients are usually depleted after a few years. If the deforestation occurs in an area of heavy rainfall, nutrients may be washed away, along with some of the soil, which further reduces nutrient availability. After a few years, the farmer usually moves on to another plot and repeats the process.

Figure 11.11 Shifting agriculture. This forest has been cleared for agriculture. Clearing land often involves burning it, which may make nutrients and soils vulnerable to erosion.
If a plot is used for a few years and then abandoned for a number of decades, over time, the soil may recover its organic content and nutrient supplies, and the vegetation may have a chance to regrow. However, population pressures may cause the land to be used too frequently to allow for its full recovery. In that case, soil productivity can decrease rapidly, leaving the land suitable only for animal grazing. In addition, the burning process oxidizes carbon, meaning that it converts it into the oxide compounds carbon monoxide (CO) and carbon dioxide (CO2). In this way, carbon from the vegetation and the soil is released into the atmosphere and ultimately contributes to higher atmospheric CO2 concentrations.

In semiarid environments, dry, nutrient-poor soils can be easily degraded by agriculture to the point at which they are no longer viable for any production at all. Irrigation can cause salinization, and topsoil is eroded away because the shallow roots of annual crops fail to hold it in place. This process is called desertification. The world map in FIGURE 11.12 shows the parts of the world that are most vulnerable to desertification. Desertification is occurring most rapidly in Africa, where the Sahara is expanding at a rate of up to 50 km (31 miles) per year. Unsustainable farming practices in northern China are also leading to rapid desertification there.

**Figure 11.12 Vulnerability to desertification.** Certain regions of the world are much more vulnerable to desertification than others. [After www.fao.org.]
The only sustainable way for people to use soil types with very low productivity is nomadic grazing, in which they move herds of animals, often over long distances, to seasonally productive feeding grounds. If grazing animals move from region to region without lingering in any one place too long, the vegetation can usually regenerate.

Shifting agriculture and nomadic grazing worked well under the conditions in which they were first developed—namely, low human population densities and subsistence farming—but as populations increase, both forms of traditional agriculture become less sustainable. Sometimes the relocation of people for political or other reasons can cause traditionally sustainable agricultural techniques to become unsustainable. For example, in the early part of the twentieth century, many subsistence farmers in Central America were relocated away from rich floodplains to mountainous areas. The plowing methods that worked in flat areas could not be sustained in the mountains because they caused severe erosion.
11.4.2 SUSTAINABLE AGRICULTURE

Is it possible to produce enough food to feed the world’s population without destroying the land, polluting the environment, or reducing biodiversity? Sustainable agriculture fulfills the need for food and fiber while enhancing the quality of the soil, minimizing the use of nonrenewable resources, and allowing economic viability for the farmer. It emphasizes the ability to continue agriculture on a given piece of land indefinitely through conservation and soil improvement. Sustainable agriculture often requires more labor than industrial agriculture, which makes it more expensive in places where labor costs are high. Practitioners of sustainable agriculture consider the improved long-term productivity of the land to be worth this extra cost, however.

Many of the practices used in sustainable agriculture are traditional farming methods (FIGURE 11.13). Subsistence farmers in India, Kenya, or Thailand typically use animal and plant wastes as fertilizer because they cannot obtain or afford synthetic fertilizers. Such traditional farmers may also practice intercropping (FIGURE 11.13a), in which two or more crop species are planted in the same field at the same time to promote a synergistic interaction between them. For example, corn, which requires a great deal of nitrogen, can be planted along with peas, a nitrogen-fixing crop. Crop rotation achieves the same effect by rotating the crop species in a field from season to season. For example, peas can be planted in a field for one year, leaving excess nitrogen in the soil to nourish the corn crop that is planted there in the following year.

![Figure 11.13](image-url) Sustainable farming methods. A variety of farming methods can be used to improve agricultural yield and retain soil and nutrients.
Intercropping trees with vegetables—a practice that is sometimes called agroforestry—allows vegetation of different heights, including trees, to act as windbreaks and catch soil that might otherwise be blown away, greatly reducing erosion (FIGURE 11.13b). The trees not only protect the vegetable crops and the soil, but also provide fruit and firewood.

Alternative methods of land preparation and use can also help to conserve soil and prevent erosion. For instance, contour plowing—plowing and harvesting parallel to the topographic contours of the land—helps prevent erosion by water while still allowing for the practical advantages of plowing (FIGURE 11.13c). Some farmers plant an autumn crop, such as winter wheat, that will sprout before frost sets in, so that the land does not remain bare between regular plantings.

### 11.4.3 NO-TILL AGRICULTURE

Soils may take hundreds or even thousands of years to develop as organic matter accumulates and soil horizons form. Conventional agriculture relies on plowing and tilling, processes that physically turn the soil upside down and push crop residues under the topsoil, thereby killing weeds and insect pupae. Critics argue, however, that plowing and tilling have negative effects on soils. Every time soil is plowed or tilled, soil particles that were attached to other soil particles or to plant roots are disturbed and broken apart and become more susceptible to erosion. In addition, repeated plowing increases the exposure of organic matter deep in the soil to oxygen. This exposure leads to oxidation of organic matter, a reduction in the organic matter content of the soil, and an increase in atmospheric CO₂ concentrations. Tilling, in addition to irrigation and overproduction, has led to severe soil degradation in many parts of the world. The world map in FIGURE 11.14 indicates areas of severe soil degradation.

**Figure 11.14**

Global distribution of soil degradation.

Soil degradation is a global problem caused by overgrazing and deforestation as well as agricultural mismanagement.

[After United Nations Environment Programme.]
No-till agriculture is designed to avoid the soil degradation that comes with conventional agricultural techniques. Farmers using this method leave crop residues in the field between seasons (FIGURE 11.15). The intact roots hold the soil in place, reducing both wind and water erosion, and the undisturbed soil is able to regenerate natural soil horizons. No-till agriculture also reduces emissions of CO2 because the intact soil undergoes less oxidation. In many cases, however, in order for no-till agriculture to be successful, farmers must apply herbicides to the fields before, and sometimes after, planting so that weeds do not compete with the crops. Therefore, the downside of no-till methods is an increase in the use of herbicides.

**Figure 11.15 No-till agriculture.** Rows of soybeans emerge between the residues of a corn crop left over from the previous season.
11.4.4 INTEGRATED PEST MANAGEMENT

Figure 11.16 Beneficial insect habitat.
Practitioners of integrated pest management often provide habitat for insects that prey on crop pests. This wasp is laying eggs in a caterpillar, which it has paralyzed.

Another alternative agricultural practice, integrated pest management (IPM), uses a variety of techniques designed to minimize pesticide inputs. These techniques include crop rotation and intercropping, the use of pest-resistant crop varieties, creating habitats for predators of pests, and limited use of pesticides.

Crop rotation and the use of pest-resistant crop varieties prevent pest infestations. Crop rotation can foil insect pests that are specific to one crop that may have laid eggs in the soil. It can also hinder crop-specific diseases that may survive on infected plant material from the previous season. Intercropping, as stated earlier, also makes it harder for specialized pests that succeed best with only one crop present to establish themselves. Farmers can also provide habitat for species that prey on crop pests.

Agroforestry encourages the presence of insect-eating birds (although birds can also damage some crops), and many herbs and flowers attract beneficial insects (FIGURE 11.16).

Figure 11.17 Effects of IPM training.
(a) IPM training of farmers in Indonesia led to a significant reduction in pesticide applications. (b) Yield improvements also occurred after the training because of the additional attention the farmers gave to their crops. [Modified after www.fao.org.]
Although IPM does use pesticides, it limits applications of pesticides through very careful observation. Farmers regularly inspect their crops for the presence of insect pests or other potential crop hazards. Pest infestations can thus be caught in early stages and treated using natural controls or smaller doses of pesticides than would otherwise be needed. These more targeted methods of pest control can result in significant savings on pesticides as well as improved yields. FIGURE 11.17, from a case study of IPM training in Indonesia, shows the difference IPM can make. Farmers who learned how to determine whether a pesticide application was warranted cut their pesticide applications—and their expenditures on pesticides—in half (FIGURE 11.17a). Yields also improved after farmers learned IPM methods (FIGURE 11.17b).

When farmers take time to inspect their fields carefully, as required by IPM methods, they often notice other crop needs, and this additional attention improves overall crop management. The trade-off for these benefits is that farmers must be trained in IPM methods and must spend more time inspecting their crops. But once farmers are trained, the extra income and reduced costs associated with IPM often outweigh the extra time they must spend in the field. IPM has been especially successful in many parts of the developing world, where the high-input industrial farming model is not feasible because labor costs are low and farmers lack financial resources.

### 11.4.5 ORGANIC AGRICULTURE

Organic agriculture is the production of crops without the use of synthetic pesticides or fertilizers. Organic agriculture follows several basic principles:

- Use ecological principles and work with natural systems rather than dominating them.
- Keep as much organic matter and as many nutrients in the soil and on the farm as possible.
- Avoid the use of synthetic fertilizers and pesticides.
- Maintain the soil by increasing soil mass, biological activity, and beneficial chemical properties.
- Reduce the adverse environmental effects of agriculture.

In the developed world, organic farming has increased in popularity over the past three decades. The U.S. Organic Foods Production Act (OFPA) was enacted as part of the 1990 farm bill to establish uniform national standards for the production and handling of foods labeled organic. The Science Applied section that follows this chapter, “How Do We Define Organic Products?” discusses organic food labeling in more detail.

For a long time, organic farms were inevitably small. Today, this is not necessarily the case. However, most organic farmers plant diverse crops and encourage beneficial insects, and to do this, they must keep their farms relatively small. Organic farmers also manage the soil carefully because if they lose soil nutrients and see a decline in the health of their crops, they have fewer options than conventional farmers have. All of these practices usually increase labor costs significantly. However, the farmers can recoup these extra labor costs by selling their harvest at a premium price to consumers who prefer to buy organic food (FIGURE 11.18).
Organic agriculture is not without some adverse environmental consequences. Because they do not use herbicides, organic farmers are less likely than conventional farmers to be able to use no-till methods successfully. And alternative pest control methods are not always environmentally friendly. For example, in order to keep crops such as carrots weed-free, organic farmers may treat the soil with a propane flamer before planting. This technique protects carrots without herbicides, but uses fossil fuel.

CHECKPOINT

- What are the goals of alternative agricultural methods?
- Describe the benefits and disadvantages of alternatives to industrial farming methods.
- What are the basic principles of organic agriculture?
11.5 Modern agribusiness includes the farming of meat and fish

In order to remain economically viable and feed large numbers of people, modern agriculture in the United States has become larger and more mechanized. While many of the goals described in the preceding sections remained in place as agricultural activities moved to a larger scale, some have been abandoned. In particular, as agriculture developed to supply meat and poultry to large numbers of people at a low cost, the primary goal became faster growth of animals.

11.5.1 HIGH-DENSITY ANIMAL FARMING

Figure 11.19 Cattle in a concentrated animal feeding operation in Texas. CAFOs are large indoor or outdoor structures that allocate a very small amount of space to each animal.

In 2009, according to the U.S. Department of Agriculture, more than 150 million animals were slaughtered for red meat, along with billions of chickens, turkeys, and ducks. Many of these animals were raised in feedlots, or concentrated animal feeding operations (CAFOs), which are large indoor or outdoor structures designed for maximum output (FIGURE 11.19). This type of high-density animal farming is used for beef cattle, dairy cows, hogs, and poultry, all of which are confined or allowed very little room for movement during all or part of their life cycle. A CAFO may contain as many as 2,500 hogs or 55,000 turkeys in a single building. By keeping animals confined, farmers
minimize land costs, improve feeding efficiency, and increase the fraction of food energy that goes into the production of animal body mass. The animals are given antibiotics and nutrient supplements to reduce the risk of adverse health effects and diseases, which would normally be high in such highly concentrated animal populations.

High-density animal farming has many environmental and health consequences. There is evidence that antibiotics given to confined animals are contributing to an increase in antibiotic-resistant strains of microorganisms that can affect humans. Waste disposal is another serious problem. An average CAFO produces over 2,000 tons of manure annually, or about as much as would be produced by a town of 5,000 people. The waste is usually used to fertilize nearby agricultural fields, but if overapplied, it can cause the same nutrient runoff problems as synthetic fertilizer. Sometimes animal wastes are stored in lagoons adjacent to feedlots. During heavy rainstorms, runoff from these lagoons can contaminate nearby waterways. Animal wastes have also been dumped, either inadvertently or intentionally, into natural waters. The U.S. Environmental Protection Agency has concluded that chicken, hog, and cattle waste has caused pollution along 56,000 km (35,000 miles) of rivers in 22 states and has caused some degree of groundwater contamination in 17 states.

MORE SUSTAINABLE ANIMAL FARMING Not all meat comes from CAFOs. Free-range chicken and beef are becoming increasingly popular in the United States. Some people find it more ethically acceptable to eat a chicken or cow that has wandered free than one that has spent its entire life confined in a small space. Free-range meat, if properly produced, is more likely to be sustainable than meat produced in CAFOs. Because the animals are not as likely to spread disease as when they are kept in close quarters, the use of antibiotics and other medications can be reduced or eliminated. The animals graze or feed on the natural productivity of the land, with little or no supplemental feeding, so less fossil fuel goes into the raising of free-range meat. Finally, manure and urine are dispersed over the range area and are naturally processed by detritivores and decomposers in the soil. As a result, there is no need to treat and dispose of massive quantities of manure. On the negative side, free-range operations use more land than CAFOs do, and the cost of meat produced using these techniques is usually significantly higher.

11.5.2

Figure 11.20 Global fish production (caught from the sea) and aquaculture. Global fish production has increased by more than 20 percent since 1980, primarily as a result of the large increase in aquaculture. Global fish production, as shown in the figure, includes both wild-caught fish and aquaculture-raised fish. [After K. M. Brander, PNAS 104 (2007): 19709–19714.]
Fish is the third major source of food for humans, after grain and meat. In many coastal areas, particularly in Asia and Africa, fish accounts for nearly all of the animal protein that some people consume. As FIGURE 11.20 shows, the global production of fish has increased by about 20 percent since 1980. This increase masks two divergent trends: a rapid increase in farmed fish production and a decrease in wild fish caught in the world’s oceans.

A fishery is a commercially harvestable population of fish within a particular ecological region. The tragedy of the commons, which we learned about in Chapter 10, is a concept that is particularly applicable to ocean fisheries. Since fish do not live their entire lives within national borders, if one individual, or even an entire country, limits its catch, others are likely to make up the difference. No country has an incentive to protect fish stocks or to attempt to replenish them because fish in the ocean do not belong to any one individual or nation. As a result, competition for fish has led to a precipitous decline in fish populations.

In 2003, the journal Nature reported a dramatic decline in the number of large predatory ocean fish caught over the past 50 years, even though both the number of fishing vessels and the amount of time spent fishing had increased over that period. Fishers are working harder, but catching fewer fish. A study in 2006 found that 30 percent of fisheries worldwide had experienced a 90 percent decline in fish populations. The decline of a fish population by 90 percent or more is referred to as fishery collapse.

Ocean harvests used to be limited by the difficulty of finding fish in a vast ocean as well as by the limited capacity of small boats and nets, but this is no longer the case. Current fishing methods make it easy to catch large numbers of fish. Factory ships can stay at sea for months at a time, processing and freezing their harvest without having to return to port. Most marine fish are now caught either by large nets pulled behind one of these ships or by very long fishing lines bearing hundreds or even thousands of baited hooks. Fishers in pursuit of high-value species such as tuna use spotter planes and sonar to locate schools, which they encircle with “purse-seine” nets. These nets can capture up to 3,000 adult tuna at a time—almost a million pounds of fish. Fish species that live on or close to the ocean bottom, as well as many shellfish, are caught in dragnets, which are weighted so that they can be pulled across the ocean floor.

Large-scale, high-tech fishing can adversely affect both target and nontarget species. Dragnets can damage ocean-bottom habitats by scouring them of coral, sea sponges, and plants. Many commercially important fish are keystone species, so a decline or loss of their populations can have cascading effects on other marine species. Intensive fishing leads to the loss of juvenile fish of the target species as well as to the loss of noncommercial species that are accidentally caught by nets and lines. This unintentional catch of nontarget species, referred to as bycatch, has significantly reduced populations of fish species such as sharks and has endangered other organisms such as sea turtles. Some countries require the use of technology that minimizes bycatch or harm to endangered species.

MORE SUSTAINABLE FISHING

In the interest of creating and supporting sustainable fisheries, many countries around the world have developed fishery management plans, often in cooperation with one another. International cooperation is particularly important because fish migrate across national borders, some marine ecosystems span national borders, and many of the world’s most important fisheries lie in international waters.
The northwestern Atlantic fisheries, for example, comprise several continental shelf ecosystems that stretch from the northeastern United States to southeastern Canada. Historically, these fisheries were among the world’s most productive. However, overfishing by international fleets of factory ships led to a catastrophic depletion of fish stocks, particularly of cod and pollock, by the early 1990s, as FIGURE 11.21 shows. The fisheries were forced to close because of the depleted stocks, and the Canadian and U.S. governments imposed a moratorium on bottom fishing in the area. The majority of the Atlantic Canadian fisheries are still closed today. Most fisheries in the United States are now open, at least for part of the year.

In response to the fishery collapse, and in order to restore the depleted stocks and manage the ecosystem as a whole, the U.S. Congress passed the Sustainable Fisheries Act in 1996. This act shifted fisheries management from a focus on economic sustainability to an increasingly conservation-minded, species-sustainability approach. The act calls for the protection of critical marine habitat, which is important for both commercial fish species and nontarget species. For many commercial species considered to be in danger, such as cod, a “sustainable” fishery means no fishing until populations recover.

One successful fishery management plan was developed in Alaska, where the commercial salmon fishery declined rapidly between 1940 and 1970. Managers first tried to increase salmon populations by limiting the fishing season, but by 1970 the season lasted less than a week, and so many fishers participated that populations continued to drop.
Figure 11.22 Commercial salmon harvest in the Alaska fishery. After a peak harvest in 1940, overfishing led to a decline in the number of fish caught. In 1973, fishery managers introduced a system of individual transferable quotas. By 1980, the fishery had rebounded.

In 1973, fishery managers introduced a system of individual transferable quotas (ITQs). Before the start of each salmon season, fishery managers establish a total allowable catch and distribute or sell quotas to individual fishers or fishing companies, favoring those that have a long-term history in the fishery. Fishers with ITQs have a secure right to catch their quota, so they have no need to spend money on bigger boats and better equipment in order to outcompete others. If fishers cannot catch enough salmon to remain economically viable, they can sell all or part of their quota to another fisher. FIGURE 11.22 shows the results: since the beginning of the ITQ program, the salmon population and harvest have increased—at times very rapidly—and costs to fishers have been reduced.

In Alaska, ITQs are sold primarily to small family-run fishing operations. In New Zealand, however, ITQs have been used effectively to control overfishing by large fishing companies. The ITQ system is being used successfully in many other fisheries around the world.

Not all fisheries are declining, but it is often difficult for consumers to know which fish are being overharvested and which are not. To help consumers make more sustainable fish choices, the Environmental Defense Fund and other organizations have compiled a list of popular food fish, dividing them into three categories depending on how sustainable their stocks are. “Best” choices include wild Alaskan salmon and farmed rainbow trout. “Worst” choices include shark and Chilean sea bass.
11.5.3 AQUACULTURE

Figure 11.23 A salmon farming operation in Chile. Uneaten food and waste released from salmon farms can cause significant nutrient input into natural marine ecosystems.

The demand for fish has increased even as wild fish catches have been falling. In response, many scientists, government officials, and entrepreneurs have been developing ways to increase the production of seafood through aquaculture: the farming of aquatic organisms such as fish, shellfish, and seaweeds. Aquaculture involves constructing an aquatic ecosystem by stocking the organisms, feeding them, and protecting them from diseases and predators. It usually requires keeping the organisms in enclosures (FIGURE 11.23), and it may require providing them with food and antibiotics. Almost all of the catfish and trout eaten in the United States, as well as half of the shrimp and salmon, are produced by aquaculture.

Proponents of aquaculture believe it can alleviate some of the human-caused pressure on overexploited fisheries while providing much-needed protein for the more than 1 billion undernourished people in the world. Aquaculture also has the potential to boost the economies of many developing countries.

Critics of aquaculture point out that it can create many environmental problems. In a typical aquaculture facility, clean water is pumped in at one end of a pond or marine enclosure, and wastewater containing feces, uneaten food, and antibiotics is pumped back into the river or ocean at the other end. The wastewater may also contain bacteria, viruses, and pests that thrive in the high-density habitat of aquaculture facilities and can infect wild fish and shellfish populations. In addition, fish that escape from aquaculture facilities may harm wild fish populations by competing with them, interbreeding with them, or spreading diseases and parasites. Overall, however, aquaculture has many promising characteristics as a means of sustainable food production.

CHECKPOINT

- What are some of the ways in which modern agribusiness produces meat and fish?
- How does the concept of the tragedy of the commons apply to fisheries?
- What is aquaculture?
Wes Jackson and the Land Institute

**Figure 11.24 Annuals and perennials.** The root system of annual wheat (left) is much smaller than that of intermediate wheatgrass, a perennial (right).

Whenever soil is plowed and prepared for another growing season, soil erosion is a problem. One long-term approach to reducing agriculture-related erosion is being explored by plant geneticist Wes Jackson, president of the Land Institute in Salina, Kansas. Jackson maintains that the single most beneficial new development in agriculture would be the development of food crops that do not need to be replanted every year.

Annual plants, such as wheat and corn, live only one season and must be replanted each year, which causes enormous disruption to the soil. In contrast, perennial plants live for multiple years, so there is no need to plow the field each year for replanting. Perennials have a longer growing season than annuals: they can continue producing roots and storing energy even after harvest, and they often emerge earlier in spring than annuals. In addition, they can rely on root systems that were established in previous years, so they can allocate more resources in the current year to the production of stems, fruits, and seeds. All of these characteristics make them more productive than annuals.

Researchers at the Land Institute are exploring a variety of ways to grow crops in systems that mimic the natural world. Using a combination of conventional selective breeding and technology, they are attempting to convert annual species such as wheat, sorghum, sunflowers, and corn into perennials. At the same time, they are collecting wild perennials such as wheatgrass, domesticating them, and selecting for higher seed yield, size, and quality (FIGURE 11.24). Through these efforts, researchers hope to assemble communities of perennial plants, animals, fungi, and microorganisms that will be stable, productive, and resistant to insect pests and diseases.

The ultimate goal of the Land Institute is to develop sustainable crops that will produce sufficient amounts of food for harvest by humans, reduce soil erosion, and reduce or eliminate the need for synthetic fertilizers, pesticides, and irrigation. The researchers have already managed to double the size of seeds of a species of wheatgrass and increase its seed production by 20 percent without losing other important qualities of the plant. They have also had some success in crossing specially treated domesticated sorghum with perennial sorghum varieties to produce progeny that are both fertile and perennial.

Critics contend that it may take many decades to develop perennial seed crops with usable products. Jackson doesn’t seem overly concerned about this. According to Jackson, “if you’re working on something you can finish in your lifetime, you’re not thinking big enough.”
References


The Land Institute: http://www.landinstitute.org

KEY IDEAS REVISITED

Identify the benefits and costs of using genetically modified organisms in agriculture.

Agricultural scientists are using genetic engineering to produce genetically modified organisms with desirable traits. GMOs can increase yields and reduce the use of pesticides. Concerns have been raised, however, about their safety for human consumption and their effects on biodiversity.

Describe alternatives to industrial farming methods.

Traditional farming techniques such as intercropping, crop rotation, agroforestry, and contour plowing can sometimes improve agricultural yields and conserve soil and other resources. No-till agriculture is another way to reduce soil erosion and degradation. Integrated pest management reduces the use of pesticides, thus saving money and reducing environmental damage. IPM requires more labor, however, and practitioners must be trained to identify potential hazards to their crops. Organic agriculture focuses on maintaining the soil and avoids the use of synthetic fertilizers and pesticides. This approach often results in more labor-intensive, smaller farms, where many alternative agricultural techniques must be applied.

Explain the environmental impacts of various approaches to raising and harvesting meat and fish.

Concentrated animal feeding operations and aquaculture facilities allow for efficient animal growth and inexpensive food production, but can have negative environmental impacts in the form of concentrated animal waste and the introduction of antibiotics and other waste products into the environment. Most fisheries in North America have been overharvested and some are now recovering.