central
CASE STUDY

Can Organic Farming and GMOs Coexist?

> **Worrying about starving future generations won't feed them. Food biotechnology will.**
>
> Advertising campaign of the Monsanto Company

> **Industrial agriculture has destroyed diverse sources of food, and it has stolen food from other species . . . using huge quantities of fossil fuels and water and toxic chemicals in the process.**
>
> Vandana Shiva, Director of the Research Foundation for Science, Technology, and Natural Resource Policy, India

Upon completing this chapter, you will be able to:

- Explain the challenge of feeding a growing human population
- Identify the goals, methods, and consequences of the Green Revolution
- Discuss how we raise animals for food, and assess the impacts that result
- Describe reasons and approaches for preserving crop diversity
- Discuss threats to pollinators and identify potential solutions
- Explore strategies for pest and weed management
- Describe the science behind genetic engineering
- Compare the benefits and costs of genetically modified foods, and assess the public debate over them
- Analyze the nature, growth, and potential of organic agriculture
- Contrast conventional industrial, organic, and biotech approaches to agriculture, and summarize potential pathways toward sustainable agriculture

Steve Marsh and Michael Baxter are neighbors and had been friends since childhood. For years, the two farmers had tended adjacent parcels of land in the small rural town of Kojonup in Western Australia. But now, flanked by their lawyers, they stared each other down in a courtroom in the full glare of the media. Their conflict captured the world's attention: It was the first time a farmer had brought a lawsuit against another farmer for "contamination" of organic fields by genetically modified crops.

Despite their legal feud, both men shared a love of farming and a commitment to the idea of sustainable agriculture. Both had tried to do the right thing for their families, society, and the environment as they made their living from the land. Their courtroom battle was a microcosm of the global debate over how we should pursue agriculture.

Marsh had turned to organic farming on his 477 hectares (ha; 1200 acres) of land because he wanted to safeguard the health of his family and the integrity of his soil and water by eliminating many of the pollution sources common to conventional industrial agriculture. He raised sheep and grew wheat, rye, and oats without using chemical pesticides or synthetic fertilizers, and he had worked diligently to obtain official certification as an organic farmer.

Baxter grew canola in the conventional way on his 900 ha (2200 acres): planting vast stands of the crop in monocultural fields, using chemical pesticides to ward off insects and weeds, and applying synthetic fertilizers to provide extra nutrients to the plants. Like most conventional farmers, he was proud to be producing large quantities of crops to help feed people inexpensively and efficiently.

In 2010, Baxter began planting Roundup Ready canola, a genetically modified (GM) crop engineered by the Monsanto Company. Like other Roundup Ready crops, this one was genetically engineered to resist the lethal effects of Monsanto's best-selling weed-killer, Roundup. With Roundup Ready crops, a farmer simply sprays Roundup throughout a field, and it kills weeds without killing the crop.

But after Baxter harvested his GM canola, Marsh discovered that some of its seeds, stalks, and leaves had blown into Marsh's fields. Under Australian law, farm produce can be labeled organic only if it is 100%

An organic produce market in Australia

A farmer tends a field of GM canola in flower free of any genetically engineered material. Consequently, inspectors de-certified the crops on 70% of Marsh's land, and as a result he was no longer able to sell his harvest as certified organic. Without the higher revenue farmers gain from organic sales, Marsh realized that he would be unable to recoup the costly investments he'd made to convert and maintain his fields to meet organic standards. Reluctantly, he judged that a lawsuit was his best remaining option.

In 2014, Marsh lost his case before Western Australia's Supreme Court. The court declared that Baxter had done nothing illegal. It said the problem was that Australia's organic certification agency held to a zero-tolerance policy and de-certified Marsh's crop even though the influx of GM material had occurred by accident. The court also ordered Marsh to pay Baxter $804,000 in legal costs. Marsh's lawyers appealed the decision, but in 2015 the Court of Appeal ruled against him. Two of that court's three judges agreed with the original ruling, but one dissented, asserting that Baxter had in fact been negligent in allowing seeds from his GM crop to reach his neighbor's land. Encouraged by the dissent, Marsh appealed to Australia's High Court, the highest court in the nation. In 2016, however, the High Court decided not to hear the case, closing off Marsh's final judicial avenue.

The protracted legal battle reverberated across Australia, which has the most land in certified organic agriculture (mostly rangeland) of any nation in the world. Thus far, only two GM crops (canola and cotton) have been approved at the national level for planting, and Australia's states vary in their policies, with some states banning these GM crops and others allowing them. Western Australia passed a law restricting them in 2003, but a new governing party in 2010 lifted the restrictions (allowing farmers like Baxter to plant GM canola). Its leaders now aim to repeal the law entirely.

Australia is the only nation to require organic farmers to meet a zero-tolerance threshold for GM-free purity, but across the world, organic farmers face the same dilemma. They pay costs up front to protect their fields from windblown pollen and seeds from GM plants, or from incursion by drifting pesticide spray from conventional industrial farming. Yet they still risk costs later if such incursion, despite their best efforts, renders their crops unsaleable as organic. A survey of 268 organic farmers across the United States in 2013 revealed that on average they pay $6500–$8500 each year in upfront preventive costs and that 16% of them had lost sales as a result of contamination, averaging losses of $4500.

Nonorganic conventional farmers who do not grow GM crops also fear such contamination. They know that Monsanto sends agents to farms to look for the presence of the company's patented GM crops on the land of farmers who did not pay for the seed. Monsanto has sued farmers for growing patented crops without payment, even if the plants appeared by accident as a result of windblown pollen or seed from neighbors.

Today farmers are increasingly fighting back in court to protect their investments. Wheat farmers in Kansas and Washington sued Monsanto in 2013 for letting its experimental GM wheat leak into the U.S. supply, because this caused millions of dollars of losses to farmers when several Asian nations that restrict GM food cut their imports of U.S. wheat as a result. In 2015, farmers sued multinational agribusiness corporation Syngenta for marketing a new strain of GM corn before getting full approval from all international buyers. The corn had gotten mixed into the U.S. supply, and China refused to import U.S. corn, resulting in perhaps $1 billion in losses.

Amid such controversies, people on all sides are trying to do their best for agriculture and our food supply. Supporters of conventional industrial agriculture point to its high yields and say theirs is the only model that can feed the world. Supporters of organic agriculture say that conventional agriculture threatens future yields with its pollution and that protecting natural resources is the best way to safeguard agriculture. Supporters of genetic engineering say that science and technology can produce novel and efficient solutions to enhance nutrition, reduce pollution, and fight hunger and poverty. In today's world, agriculture is complex and fast changing. In this chapter, we explore the various pathways available to us in the pursuit of sustainable farming and grazing.

The Race to Feed the World

As the human population continues to grow, we can expect our numbers to swell past 9 billion by the middle of this century. For every four people living today, there will be five in 2050. Feeding 2 billion additional mouths while protecting the soil, water, and ecological resources that underpin agriculture will require the large-scale embrace of farming and grazing practices that are more sustainable than those we currently use.

The industrialization of agriculture (p. 212) has boosted our production of food and fiber to extraordinary levels. By intensifying our inputs of energy and resources and by managing production efficiently at immense scales, we have increased our agricultural output beyond what any farmer or rancher of the past would have imagined. Yet our high-input industrial agriculture also has brought pollution and resource depletion on unprecedented scales. The environmental impacts of high-input industrial agriculture now threaten to roll back our gains, calling into question whether the industrial model can be sustained in the long term. An alternative vision is one of low-input agriculture, such as organic agriculture conducted at more local scales. This model reduces impacts but sacrifices economic efficiency; as a result, many people wonder if it can produce enough food, at low enough cost, to feed the world's billions. Alongside the debate over which model is more sustainable, the quickly evolving science and technology of genetic engineering is offering intriguing solutions while also raising questions and anxieties.

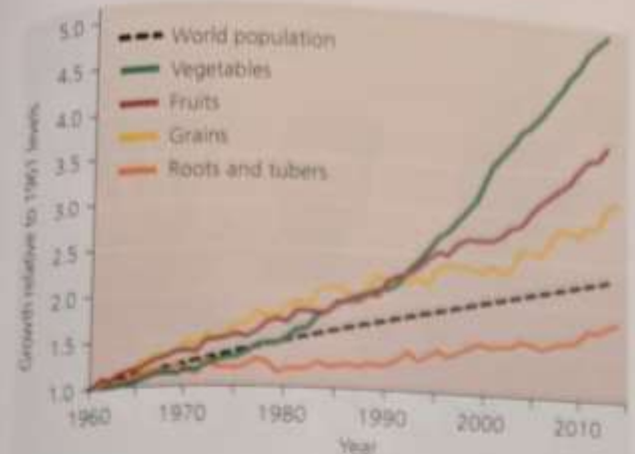

FIGURE 10.1 Global production of most foods has risen more quickly than world population. This means that we have produced more food per person each year. The data lines show cumulative increases relative to 1961 levels (for example, a value of 2.0 means twice the 1961 amount). Food is measured by weight. *Data from UN Food and Agriculture Organization (FAO).*

We are producing more food per person

Over the past half-century, our ability to produce food has grown faster than our global population (**FIGURE 10.1**). We have increased food production by devoting more fossil fuel energy to agriculture; intensifying our use of irrigation, fertilizers, and pesticides; planting and harvesting more frequently; cultivating more land; and developing (mostly through traditional crossbreeding, partly through genetic engineering) more productive crop and livestock varieties.

Improving people's quality of life by producing more food per person is a monumental achievement of which humanity can be proud. However, ensuring that our food production can be sustained depends on conserving soil, water, and biodiversity by using careful agricultural practices. Today many of the world's soils are in decline, and most of the planet's arable land has already been claimed (Chapter 9). Hence, even though agricultural production has outpaced population growth so far, we have no guarantee that this will continue.

We face undernutrition, overnutrition, and malnutrition

Despite our rising food production, nearly 800 million people worldwide do not have enough to eat. These people suffer from **undernutrition,** receiving fewer calories than the minimum dietary energy requirement. As a result, every 5 seconds, somewhere in the world, a child starves to death. In most cases, poverty limits the amount of food people can buy. One out of every seven of the world's people lives on less than $1.25 per day, and one out of three lives on less than $2 per day, according to World Bank estimates. Political obstacles, regional conflict and wars, and inefficiencies in distribution contribute significantly to hunger as well.

Most people who are undernourished live in the developing world. However, hunger is also a problem in the United States, where the U.S. Department of Agriculture (USDA) has classified 49 million Americans as "food insecure," lacking the income required to reliably procure sufficient food. Agricultural scientists and policymakers worldwide pursue a goal of **food security,** the guarantee of an adequate, safe, nutritious, and reliable food supply available to all people at all times.

The good news is that globally the number of people suffering from undernutrition has been falling since the 1960s. The percentage of people who are undernourished has fallen even more (**FIGURE 10.2**). We still have a long way to go to eliminate hunger, but these positive trends are encouraging.

Although nearly 800 million people lack access to adequate food, many others consume more than is healthy and suffer from **overnutrition,** receiving too many calories each day. Overnutrition is a problem in developed nations such as the United States, where food is abundant, junk food is cheap, and people tend to lead sedentary lives with little exercise. As a result, more than one in three U.S. adults are obese, according to the Centers for Disease Control and Prevention. Across the world as a whole, the World Health Organization estimates that 39% of adults are overweight and that of these, one-third are obese. Excessive weight can lead to heart disease, diabetes, stroke, some types of cancer, and other health problems. The growing availability of highly processed foods (which are often calorie-rich, nutrient-poor, and inexpensive) suggests that overnutrition will remain a challenge.

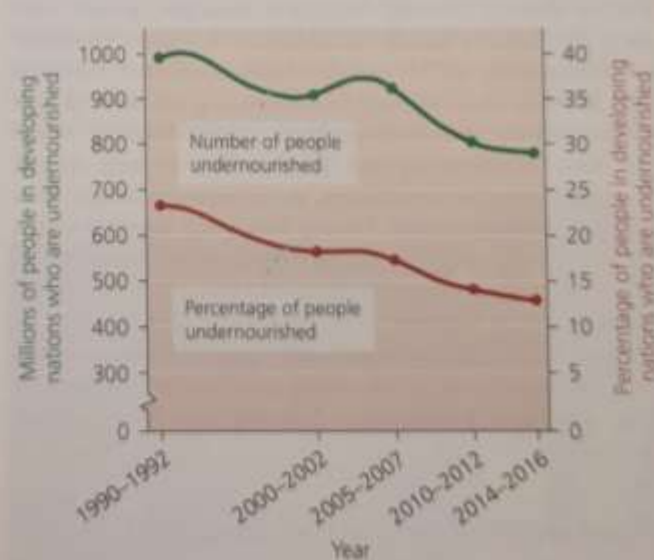

FIGURE 10.2 The number and the percentage of people in the developing world who suffer undernutrition have each been declining. *Data from Food and Agriculture Organization of the United Nations, 2015. The state of food insecurity in the world, 2015. Rome: FAO.*

DATA Q Explain how the percentage of undernourished people can have decreased slightly between 2000–2002 and 2005–2007, while the absolute number of undernourished people increased slightly during the same period.

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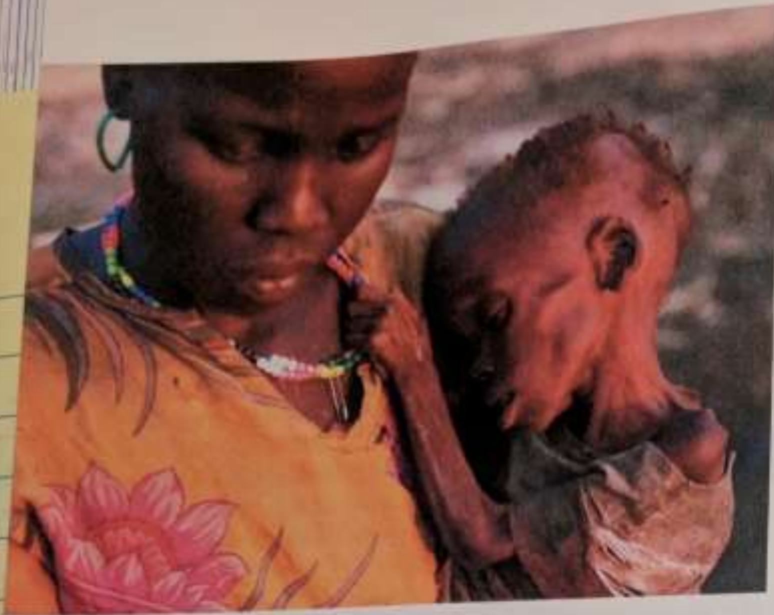


FIGURE 10.3 Millions of children suffer from forms of malnutrition, such as kwashiorkor and marasmus.

FIGURE 10.4 Norman Borlaug helped launch the Green Revolution. The high-yielding, disease-resistant wheat that he bred helped boost agricultural productivity in developing countries.

Just as the *quantity* of food a person eats is important for health, so is the *quality* of food. **Malnutrition,** a shortage of nutrients the body needs, occurs when a person fails to obtain a complete complement of essential proteins (p. 27), lipids (p. 28), vitamins, or minerals. Malnutrition can lead to disease (**FIGURE 10.3**). For example, people who eat a diet high in starch but deficient in protein or essential amino acids (p. 27) can develop *kwashiorkor*. Children who have recently stopped breast-feeding are most at risk for developing kwashiorkor, which causes bloating of the abdomen, deterioration and discoloration of hair, mental disability, immune suppression, developmental delays, anemia, and reduced growth. Protein deficiency together with a lack of calories can lead to *marasmus,* which causes wasting or shriveling among millions of children in the developing world. A deficiency of iron in the diet can lead to anemia, which causes fatigue and developmental disabilities; iodine deficiency can cause swelling of the thyroid gland and brain damage; and vitamin A deficiency can lead to blindness.

The Green Revolution boosted agricultural production

The desire for greater quantity and quality of food for the world's growing population led in the mid- and late-20th century to the **Green Revolution** (p. 212), which introduced new technology, crop varieties, and farming practices to the developing world. Agricultural scientists had realized that farmers could not go on forever converting additional land to increase production, so they devised methods and technologies to increase crop yields on existing cultivated land. As a result, yields rose dramatically in industrialized nations. For instance, the average acre of U.S. corn field raised its corn output fivefold during the 20th century. Many people viewed such growth in production and efficiency as key to ending starvation in developing nations.

The transfer of technology and practices to the developing world that marked the Green Revolution began in the 1940s, when American agricultural scientist Norman Borlaug introduced Mexico's farmers to a specially bred type of wheat (**FIGURE 10.4**). This strain of wheat produced large seed heads, was resistant to diseases, was short in stature to resist wind, and produced high yields. Within two decades of planting this new crop, Mexico tripled its wheat production and began exporting wheat. The stunning success of this program inspired others. Borlaug—who won the Nobel Peace Prize for his work—took his wheat to India and Pakistan and helped transform agriculture there as well.

Soon many developing countries were doubling, tripling, or quadrupling their yields using selectively bred strains of wheat, rice, corn, and other crops from industrialized nations. When Borlaug died in 2009 at age 95, he was widely celebrated as having saved more lives than anyone in history—estimated to be as many as a billion.

Industrialized agriculture has brought mixed consequences

Along with the new grains, developing nations imported the methods of industrial agriculture. They began applying large amounts of synthetic fertilizers and chemical pesticides on their fields, irrigating crops generously with water, and using more machinery powered by fossil fuels. From 1900 to 2000, people increased energy inputs into agriculture by 80 times while expanding the world's cultivated area by just one-third.

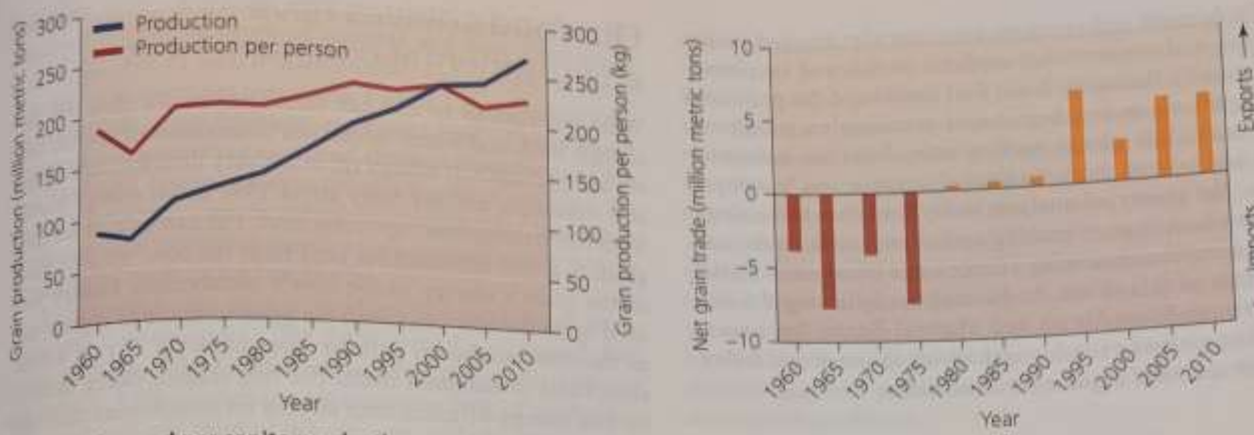


FIGURE 10.5 Green Revolution technology enabled India to boost its grain production. India's production grew faster than its population **(a)**, so that grain per person increased from the 1960s to the 1990s. As a result **(b)**, India was able to stop importing grain and begin exporting it to other nations. *Data from UN Food and Agriculture Organization (FAO).*

This high-input agriculture succeeded in producing more corn, wheat, rice, and soybeans from each hectare of land. Intensified agriculture saved millions in India from starvation in the 1970s and turned that nation into a net exporter of grain (**FIGURE 10.5**).

The environmental and social impacts of these developments have been mixed. On the positive side, intensifying the use of already-cultivated land reduced pressures to convert additional lands for cultivation. Between 1961 and 2013, global food production more than tripled and per-person food production rose 48%, while area converted for agriculture increased only 11%. In this way, the Green Revolution helped preserve biodiversity and natural ecosystems by preventing a great deal of deforestation and habitat destruction. On the negative side, the intensified use of fossil fuels, water, inorganic fertilizers, and synthetic pesticides has worsened pollution, topsoil erosion, and soil and water quality (Chapter 9).

In today's conventional industrial agriculture, crops are planted in monocultures, large expanses of single crop types (p. 212; **FIGURE 10.6**). This makes planting and harvesting efficient and thereby increases output. However, monocultures also reduce biodiversity over large areas, because many fewer wild organisms are able to live in monocultures than in native habitats or in traditional small-scale polycultures. Moreover, when all plants in a field are of the same species (and thus genetically similar), they are susceptible to viral diseases, fungal pathogens, or insect pests that can multiply and spread quickly from plant to plant. For this reason, monocultures bring risks of catastrophic failure.

Today, yields are declining in some regions targeted by the Green Revolution, likely due to soil degradation from the heavy use of fertilizers, pesticides, and irrigation. Moreover, wealthier farmers with larger holdings of land were best positioned to invest in Green Revolution technologies. As a result, many low-income farmers who could not afford these technologies were driven out of business and moved to cities, adding to the immense migration of poor rural people to urban areas of the developing world (p. 333).

How can we achieve sustainable agriculture?

Most experts feel that to sustain our population in the long run we will need to begin raising crops and livestock in ways that are less polluting and less resource-intensive. **Sustainable agriculture** (p. 212) consists of farming and grazing that maintain the healthy soil, clean water, pollinators, genetic diversity, and other resources needed for the production of crops and livestock over the long term. The

FIGURE 10.6 Monocultures improve the efficiency of planting and harvesting but are susceptible to outbreaks of pests. Armyworms (**inset**) attack corn fields like this one.

world's farmers and ranchers have already adopted many strategies and conservation methods to this end (explored in Chapter 9). Reducing fossil fuel inputs and the pollution these inputs cause is a key aim of sustainable agriculture, and to many this means moving away from the industrial model and toward more traditional organic and low-input models. Yet plenty of analysts today feel that technology offers our best hope of making agriculture sustainable, and that the genetic engineering of crops and livestock is a vital component of this effort. As Australians following the dispute between Steve Marsh and Michael Baxter have seen, competing visions exist for agriculture in our world today, and there are valid arguments on all sides.

Raising Animals for Food

Food from cropland agriculture makes up a large portion of the human diet, but most of us also eat animal products. As our population has grown, consuming meat and other animal products has come to have significant environmental, social, and economic impacts. How we respond to demand for animal products affects our society's ecological footprint and our quest for sustainable agriculture.

Consumption of animal products is growing

As wealth and global commerce have increased, so have humanity's production and consumption of meat, milk, eggs, and other animal products (**FIGURE 10.7**). Worldwide, more than 30 billion domesticated animals are raised and slaughtered for food each year. Global meat production has increased more than fivefold since 1950, and per capita meat consumption has doubled. The Food and Agriculture Organization of the United Nations (FAO) predicts that as developing nations become wealthier, per capita meat consumption could nearly double again by the year 2050.

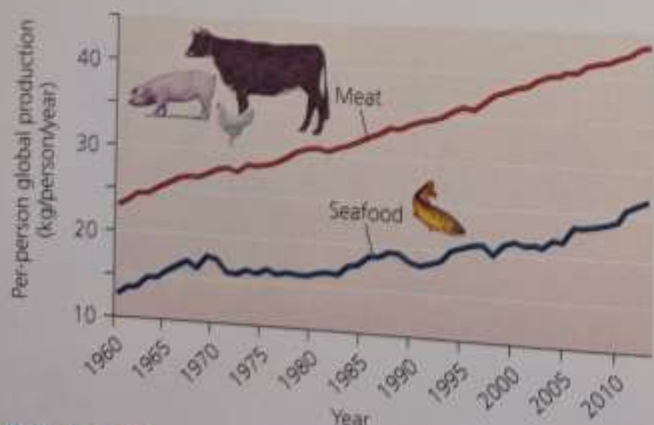


FIGURE 10.7 Per-person production of meat from farmed animals and of seafood has risen steadily worldwide. *Data from UN Food and Agriculture Organization (FAO).*

Our food choices have environmental consequences

What we choose to eat has ramifications for how we use energy, land, and water. Recall our discussions of trophic levels and pyramids of energy (p. 80). Every time that one organism consumes another, only about 10% of the energy moves from one trophic level up to the next. For example, if we feed grain to a cow and then eat beef from the cow, we lose most of the grain's energy to the cow's metabolism. Energy was used up as the cow converted the grain to tissue as it grew and as the cow conducted cellular respiration (p. 31) on a constant basis to maintain itself. For this reason, eating meat is far less energy-efficient than relying on a vegetarian diet, and it leaves a far greater ecological footprint.

In contrast, if we eat lower on the food chain (a more vegetarian diet with fewer animal products), we put a greater proportion of the sun's energy to use as food for ourselves. The lower on the food chain we eat, the smaller is our ecological footprint, and the more of us Earth can support.

In addition, some animals convert grain feed into milk, eggs, or meat more efficiently than others (**FIGURE 10.8**).

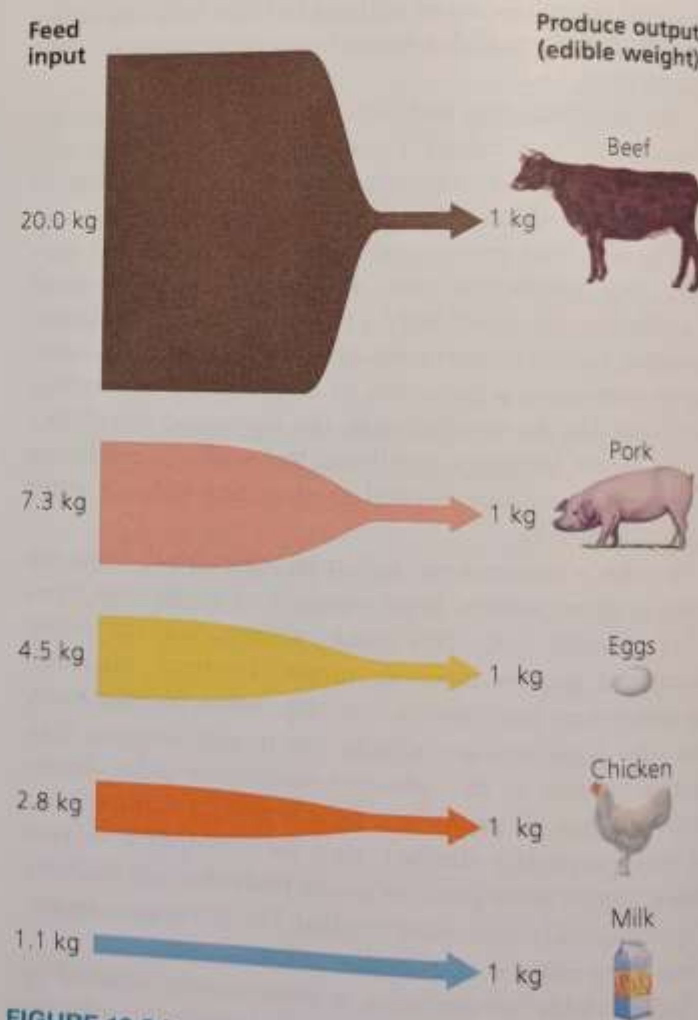


FIGURE 10.8 Producing different animal food products requires different amounts of animal feed. Twenty kilograms of feed must be provided to cattle to produce 1 kg of beef. *Data from Smil, V., 2001. Feeding the world: A challenge for the twenty-first century. Cambridge, MA: MIT Press.*

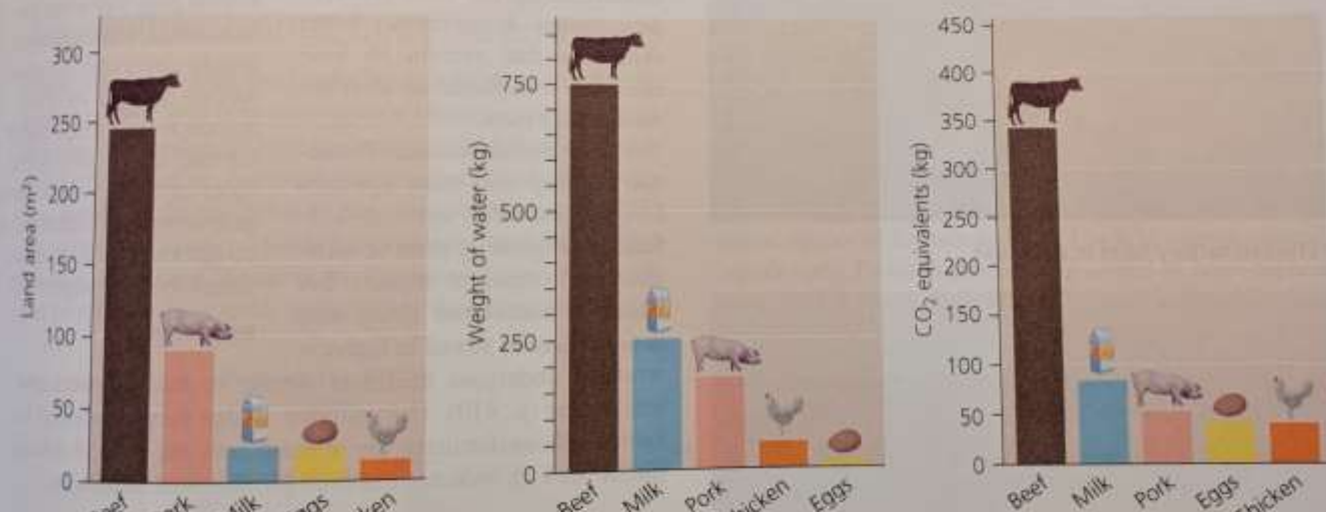
Scientists have calculated relative energy-conversion efficiencies for different types of animals and have used these to infer the area of land (FIGURE 10.9a) and weight of water (FIGURE 10.9b) required to produce 1 kg (2.2 lb) of edible protein from milk, eggs, chicken, pork, and beef. The research illustrates that producing eggs and chicken meat requires the least land and water, whereas producing beef requires the most. These differences in efficiency demonstrate that when we choose what to eat, we are also choosing indirectly how to use resources such as land and water.

Eating meat and animal products has additional environmental consequences. The FAO recently estimated that livestock in the United States account for 55% of the nation's soil erosion, 37% of pesticide applications, 50% of antibiotics consumed, and one-third of the nitrogen and phosphorus pollution in U.S. waterways.

Our diets also have consequences for climate change, because livestock are a major source of greenhouse gases that lead to global warming (p. 482). FIGURE 10.9c shows the amount of emissions (in carbon dioxide equivalents) released in the production of 1 kg (2.2 lb) of edible protein from milk, eggs, chicken, pork, and beef. Again, beef exerts the largest footprint. Livestock release methane and nitrous oxide in their metabolism and waste. Nitrous oxide is also released from certain crops used to feed animals, and from fertilizers applied to those crops. Carbon dioxide is released to the atmosphere when forests are cleared for ranching or for growing feed, as well as when fossil fuels are burned to grow feed or transport animals. The FAO reports that across the world, livestock agriculture contributes 5% of our carbon dioxide emissions, 44% of our methane emissions, and 53% of our nitrous oxide emissions. Altogether, this represents 14.5% of the emissions driving climate change—a larger share than automobile transportation! On a brighter note, the FAO also concludes that we can reduce greenhouse gas emissions from livestock by 30% by the widespread adoption of clean and efficient technologies and practices already being used by the most resourceful producers.

Feedlots have benefits and costs

In traditional agriculture, livestock are kept by farming families near their homes or are grazed on open grasslands by nomadic herders or sedentary ranchers. These traditions survive today, but the advent of industrial agriculture and the rising demand for meat, milk, and eggs has brought an additional method of raising animals for food. **Feedlots,** also known as *factory farms* or *concentrated animal feeding operations*, are huge pens designed to deliver energy-rich



(a) Land required to produce 1 kg of protein

(b) Water required to produce 1 kg of protein

(c) Greenhouse gas emissions released in producing 1 kg of protein

FIGURE 10.9 **Producing different types of animal products requires different amounts of (a) land and (b) water—and releases different amounts of (c) greenhouse gas emissions.** Raising cattle for beef exerts the greatest impacts in all three ways. *Data (a, b) from Smil, V., 2001. Feeding the world: A challenge for the twenty-first century. Cambridge, MA: MIT Press; and (c) from FAO, 2015. Global Livestock Environmental Assessment Model (GLEAM).*

DATA Answer the following in terms of protein, pound for pound.

- How many times more land does it take to produce beef than chicken?
- How many times more water does beef require, compared with chicken?
- How many times more greenhouse gas emissions does beef release, relative to chicken?

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food to animals living at high densities (**FIGURE 10.10**). Today nearly half the world's pork and most of its poultry come from feedlots.

Feedlots allow for economic efficiency and greater food production, and this makes animal products affordable to more people. However, feedlot animals are generally fed grain grown on cropland. One-third of the world's cropland is now devoted to growing feed for animals, and 45% of global grain production goes to feed livestock and poultry. This elevates the price of staple grains and can endanger food security for the poor.

For environmental quality, feedlots offer one very significant benefit: Taking cattle and other livestock off pastureland and concentrating them in feedlots reduces grazing impacts across large areas of the landscape (p. 227). Animals that are densely concentrated in feedlots will not contribute to overgrazing.

At the same time, intensified animal production at feedlots can result in intensive pollution. Livestock produce prodigious amounts of manure and urine, and the highly concentrated waste from feedlots can pollute surface water and groundwater. Rich in nitrogen and phosphorus, livestock waste is a common cause of eutrophication (pp. 109, 406). This waste may also release bacterial and viral pathogens that can sicken people, including *Salmonella*, *Escherichia coli*, *Giardia*, *Microsporidia*, *Pfiesteria*, and pathogens that cause diarrhea, botulism, and parasitic infections.

The crowded conditions under which animals are kept in feedlots necessitate heavy use of antibiotics to control disease. Overuse of antibiotics can cause microbes to evolve resistance to the antibiotics (just as pests evolve resistance to pesticides; p. 247). This makes the drugs less effective, and leads feedlot managers to increase dosages and switch to ever-stronger antibiotics. Hormones are administered to livestock as well, and metals are added to feed to spur growth. Livestock excrete most of these chemicals, which end up in wastewater and may be transferred up the food chain in downstream ecosystems. Some chemicals that remain in livestock are transferred to us when we eat their meat.

The Environmental Protection Agency and state agencies keep a watchful eye on U.S. feedlots, regulating them to minimize environmental impacts. For example, wastewater along with manure may be stored in lagoons, where it undergoes treatment similar to that of municipal wastewater (p. 410). The resulting sludge may be applied to farm fields as fertilizer (or injected into the ground where plants need it), reducing the need for chemical fertilizers.

weighing the ISSUES

Feedlots and Animal Rights

Animal rights advocates denounce factory farming because they argue that it mistreats animals. Chickens, pigs, and cattle are crowded together in small pens their entire lives, fattened up, and slaughtered. Should we concern ourselves with the quality of life of the animals that constitute part of our diet? Do you think animal rights concerns are as important as environmental concerns? Are conditions at feedlots a good reason for being vegetarian?

(a) Chicken factory farm in Arkansas

(b) Cattle feedlot in Colorado

FIGURE 10.10 Most meat eaten in the United States comes from animals raised in feedlots or factory farms. These facilities house thousands of animals such as **(a)** chickens or **(b)** cattle at high densities. The animals are dosed liberally with antibiotics to control disease.

We use aquaculture to raise seafood

Part of the typical human diet consists of aquatic organisms. However, wild fish populations are plummeting throughout the world's oceans as increased demand and new technologies lead us to overexploit marine fisheries (pp. 433–438). As a result, raising fish and shellfish on "fish farms" may be one of the best ways to meet our growing demand for these foods (**FIGURE 10.11**).

The cultivation of aquatic organisms for food in controlled environments, called **aquaculture,** is now being pursued with more than 220 freshwater and marine species, ranging from fish to shrimp to clams to seaweeds (**FIGURE 10.12**). Many aquatic species are raised in open water in large, floating netpens. Others are raised in ponds or holding tanks.

FIGURE 10.11 People practice many types of aquaculture. Here, fish-farmers tend their animals at a fish farm in China.

Aquaculture is our fastest-growing type of food production; global output has increased 10-fold in just the past 30 years. Most widespread in Asia, aquaculture today produces more than $160 billion worth of food and provides half of the fish and two-thirds of the shellfish that people eat.

Aquaculture brings benefits and costs

Aquaculture increases food supplies and helps ensure reliable protein sources, thus improving people's food security. Aquaculture also helps reduce fishing pressure on wild fish stocks, many of which, as we've discussed, are overharvested and declining. Reducing fishing pressure also lessens bycatch (p. 435), the unintended catch of nontarget organisms that results from commercial fishing. Aquaculture consumes fewer fossil fuels and provides a safer work environment than does commercial fishing. Fish farming can produce up to 10 times more fish per unit area than is harvested from waters of the continental shelf and up to 1000 times more than from the open ocean.

When practiced on a small scale by families or villages, as in much of the developing world, community-based aquaculture can be sustainable, and its compatibility with other activities can make it an effective path toward sustainable agriculture (p. 263). For instance, uneaten fish scraps make excellent fertilizers for crops, and food waste can be fed to fish.

At large scales, industrialized aquaculture produces ample amounts of food but also exerts environmental impacts. Dense concentrations of farmed animals can incubate disease, which necessitates antibiotic treatment, results in expense, and can reduce food security. Industrial-scale shrimp farming along tropical coastlines has destroyed large areas of valuable mangrove forest and has polluted coastal waters. Indeed, aquaculture can produce remarkable amounts of waste, both from the farmed organisms and from feed that goes uneaten and decomposes in the water. As with feedlot livestock, commercially farmed fish often are fed grain, which is energy-inefficient and can reduce food supplies for people. Farmed fish are also sometimes fed fish meal made from wild ocean fish such as herring and anchovies, whose harvest may place additional stress on wild populations. For all these reasons, industrial-scale aquaculture can leave a large ecological footprint.

If farmed aquatic organisms escape into ecosystems where they are not native, they may spread disease to native stocks or may outcompete native organisms for food or habitat. This is happening with several Asian carp species farmed in the central United States that have escaped and whose growing populations are altering ecosystems and harming fisheries. Such concerns delayed government approval of genetically engineered Atlantic salmon, which in 2015 became the first GM animal approved for sale as food. The GM salmon created by AquaBounty Technologies are engineered to grow especially fast (**FIGURE 10.13**). Such GM fish could help reduce fishing

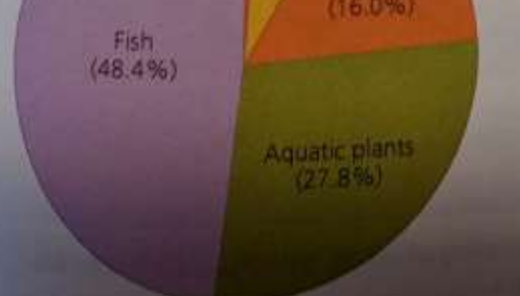


FIGURE 10.12 Aquaculture involves many types of fish, but also a wide diversity of other marine and freshwater organisms. Data from UN Food and Agriculture Organization (FAO).

FIGURE 10.13 Transgenic salmon (top) grow faster than wild salmon of the same species. They often reach a larger size; these two fish are the same age.

pressures on wild stocks, but critics contend that they might also—if they escape into the wild—outcompete their wild relatives, interbreed with them, or spread disease to them. In response, AquaBounty has promised to cultivate only sterile females and to raise the fish in freshwater tanks isolated from rivers and oceans.

Preserving Crop Diversity and Pollinators

Industrial agriculture puts pressure on many of the ecological resources that support our food production. Among these resources are the genetic diversity of crop plants and the populations of pollinating insects that help plants reproduce.

Crop diversity provides insurance

In a modern industrial monoculture, all crop plants in a field are of the same species and genetically similar. This places all our eggs in one basket, such that any single catastrophe might potentially wipe out an entire crop. Monocultures also have narrowed the human diet by reducing the diversity of crops we grow—both the types of crops and the diversity of genetic variants within each crop type. Although expanded international trade provides most individual people access to a wider diversity of foods than were available in the past, for humanity as a whole fully 90% of the food consumed now comes from just 15 crop species and 8 livestock species—a drastic reduction in diversity from earlier times. One can find examples with every food type in every region of the world. Only 30% of the maize varieties that grew in Mexico in the 1930s exist today. The number of wheat varieties in China dropped from 10,000 in 1949 to 1000 by the 1970s. In the United States, apples and other fruit and vegetable crops have decreased in diversity by 90% in less than a century.

Mass-market forces contribute to the trend toward lesser diversity because commercial food processors prefer items to be uniform in size and shape for convenience, and because consumers are often wary of what they perceive as unusual-looking food products.

Preserving the integrity of diverse native crop variants gives us a bulwark against the potential failure of our homogenized commercial crops. Every crop has a wild ancestral species from which it was domesticated, and most crops have had a complex evolutionary history, with people creating many *landraces* (variants adapted to local conditions) over the centuries. The wild relatives of crop plants and their local landraces contain a diversity of genes that we may someday need to introduce into our commercial crops (through cross-breeding or genetic engineering) to confer resistance to disease or pests or to meet other unforeseen challenges.

For instance, all the world's maize (corn) arose from a wild grass species from the highlands of Mexico. Generations of Mexican farmers have selectively bred varieties of maize, creating hundreds of local landraces (**FIGURE 10.14a**). When researchers 15 years ago presented evidence that genetically engineered corn might be interbreeding with these landraces, the world's agricultural scientists refocused attention on the importance of preserving genetic diversity of the Mexican landraces, as a form of insurance for the world's corn.

Likewise, the potato blight that devastated Ireland in the 1840s and forced the emigration of so many Irish farmers to America occurred because every potato in Ireland was derived from just one or a few strains. These strains originated in the Andes Mountains in South America, where potatoes were first domesticated. Today thousands of amazingly diverse potato varieties survive in the Andes (**FIGURE 10.14b**), cultivated in backyard gardens and serving as a reservoir of genetic diversity that can protect the world's potato crops. Safeguarding regions and cultures that maintain a wealth of crop diversity is one way to conserve the genetic resources so vital to our long-term success with agriculture.

Seed banks are living museums

Another way to preserve genetic assets for agriculture is to collect and store seeds from diverse crop varieties. This is the work of **seed banks,** institutions that preserve seed types as

(a) A sampling of maize varieties from Mexico

(b) A sampling of potato varieties from the Andes

FIGURE 10.14 Local landraces preserve genetic diversity for crop plants. Mexico hosts numerous varieties of maize **(a)** bred by farmers over centuries, whereas Peru and other Andean nations host thousands of types of potatoes **(b)** showing striking variety.

FIGURE 10.15 **The "doomsday seed vault" in Arctic Norway stores seed samples as insurance against global agricultural catastrophe.**

a kind of living museum of genetic diversity. These facilities keep seed samples in cold, dry conditions to keep them viable, and they plant and harvest them periodically to renew the stocks.

Examples of seed banks include the Millennium Seed Bank in the United Kingdom; the U.S. National Seed Storage Laboratory at Colorado State University; Seed Savers Exchange in Iowa; Native Seeds/SEARCH in Tucson, Arizona; and the Wheat and Maize Improvement Center in Mexico. In total, 1400 such facilities house 1–2 million distinct types of seeds worldwide.

The most renowned seed bank is the so-called doomsday seed vault established in 2008 on the island of Spitsbergen in Arctic Norway. The internationally funded Svalbard Global Seed Vault (FIGURE 10.15) is storing millions of seeds from around the world (spare sets from other seed banks) as a safeguard against global agricultural calamity—"an insurance policy for the world's food supply." This secured, refrigerated facility is built deep into a mountain in an area of permanently frozen ground. The site has no tectonic activity, has little natural radiation or humidity, and is high enough above sea level to stay dry even if climate change melts all the planet's ice. The doomsday seed vault is an admirable effort, but we would be well advised not to rely on it to save us. Far better to manage our agriculture wisely and sustainably so that we never need to break into the vault!

Bee declines make pollinator conservation urgent

Just as genetic diversity in crops is a resource on which agriculture relies, so are healthy populations of the insects and other animals that pollinate many of our crops (pp. 219–220). Farmers in the United States alone gain an estimated $15 billion per year in pollination services from the introduced European honeybee that beekeepers have domesticated for use with crops (see Figure 9.12, p. 220), and more than $3 billion per year from many of the nation's 4000 species of wild native bees. However, scientific data indicate that populations of honeybees and of wild native bees are declining steeply across North America. As bees disappear, we lose their services and risk lowered crop yields.

Scientists studying the pressures on bees, butterflies, and other pollinators are concluding that they are suffering a "perfect storm" of stresses—many of which result from industrial agriculture. A direct source of mortality is the vast arsenal of chemical insecticides we apply to crops, lawns, and gardens to kill pest insects. All insects are vulnerable to these poisons, so when we try to control pests, we also end up killing beneficial insects such as bees. Pollinators have suffered loss of habitat and flower resources for decades, but this has grown worse recently as weed-killers like Roundup have eliminated weeds from farm monocultures, depriving pollinators of a diversity of nectar and pollen sources. Bees are also being attacked by novel parasites and pathogens that, like many invasive species (pp. 86, 287), have been moved around the world by human travel and trade. In particular, two accidentally introduced parasitic mites have swept through honeybee populations in recent years, decimating hives and pushing beekeepers toward financial ruin.

Researchers are finding that these multiple sources of stress seem to interact and cause more damage than the sum of their parts. For example, pesticide exposure and difficulty finding food might weaken a bee's immune system, making it more vulnerable to parasites. Any or all of these factors may possibly play a role in what is being called **colony collapse disorder,** a mysterious malady that for the past decade has destroyed up to one-third of all honeybees in the United States each year (FIGURE 10.16).

Fortunately, we have a number of solutions at hand to help restore bee populations. By retaining or establishing

FIGURE 10.16 **Honeybees have been dying off in huge numbers in recent years.** Chemical insecticides, introduced parasites and pathogens, and loss of habitat and flower resources are likely all to blame.

FIGURE 10.17 Farmers can help conserve pollinating insects by leaving buffer strips of flowering native plants along the edges of their cultivated fields.

wildflowers and flowering shrubs in or near farm fields, farmers can provide bees a refuge and a source of diverse food resources (FIGURE 10.17). Organic farmers such as Steve Marsh often plant such buffer strips to protect against incursion of pesticides or GM material from neighbors, and conventional farmers sometimes plant buffer strips to protect streams and receive subsidies under conservation programs (p. 230). Encouraging flowers on highway rights-of-way can provide resources to pollinators while beautifying roadsides, and the U.S. Federal Highway Administration is working with the Xerces Society, a pollinator conservation non-profit group, to restore and create pollinator habitat along the nation's highways. In addition, farmers can decrease their use of chemical insecticides by using biocontrol or integrated pest management (pp. 248–249). Homeowners can help pollinators by reducing or eliminating the use of pesticides, tending gardens of flowering plants, and providing nesting sites for bees. These solutions and others have been embraced in a national strategy put forth in 2015 by the Obama administration's Pollinator Health Task Force.

Controlling Pests and Weeds

Although pollinating insects are beneficial for agriculture, many other organisms can weaken or destroy our crops and livestock. Some insects feed on crop plants, some pathogens attack livestock or crops, and some plants compete with crop plants for sun, water, and nutrients. Anyone who has ever planted a crop or raised animals has struggled with these natural adversaries, and any pursuit of sustainable agriculture will need to find safe and effective ways of limiting losses to them.

"Pests" and "weeds" hinder agriculture

What people term a **pest** is any organism that damages crops or livestock. What we term a **weed** is any plant that competes with our crops. These are subjective terms that we define entirely by our own economic interests. There is nothing inherently malevolent about a pest or a weed. These organisms are simply growing and behaving naturally, adapted to survive and reproduce, like any other animal or plant. They just happen to affect our farm productivity in doing so.

Throughout the history of agriculture, the insects, mites, rats, fungi, and viruses that attack our crops have taken advantage of the ways we cluster food plants in agricultural fields. Pests pose an especially great threat to monocultures, because a pest adapted to specialize on a crop can move easily from plant to plant (see Figure 10.6). From the perspective of an insect that feeds on corn, grapes, or apples, encountering a grain field, vineyard, or orchard is like discovering an endless buffet. In a natural ecosystem, each organism's population is kept in check by its predators, competitors, parasites, and pathogens—but in an industrial monoculture, the abundance of one type of food and the lack of other habitats can allow a pest population to flourish, unhindered by its natural enemies.

We have developed thousands of chemical pesticides

Because industrial monocultures limit the ability of natural enemies to control pest populations, farmers have felt the need to introduce some type of pest control to produce food economically at a large scale. In the past half-century, most farmers have turned to chemicals to suppress pests and weeds. In that time we have developed thousands of synthetic chemicals to kill insects (*insecticides*), plants (*herbicides*), and fungi (*fungicides*). Such poisons are collectively termed **pesticides.**

All told, nearly 400 million kg (900 million lb) of active ingredients from conventional pesticides are applied in the United States each year—almost 3 pounds per person. Four-fifths of this total is applied on agricultural land (FIGURE 10.18). Since 1960, pesticide use has risen fourfold worldwide. Usage in industrialized nations has leveled off, but it continues to rise in the developing world. Today more than $44 billion is expended annually on pesticides across the world.

FIGURE 10.18 Synthetic chemical pesticides are widely applied to crops in conventional industrial agriculture.

Pesticides boost food production but also have negative impacts

Chemical pesticides have helped to greatly increase our food production. They help us control pests in our homes, and they continue to protect millions of people in developing nations from insect-borne diseases such as malaria. However, exposure to synthetic pesticides can have health consequences for people (Chapter 14). Especially vulnerable are farm workers, who experience high levels of pesticide exposure, and children, whose brains and bodies are growing and developing. We all encounter and ingest chemical pesticide residues when we eat non-organic produce we buy at the grocery store, and pesticides leave residues and breakdown products in the soil, water, and air, affecting organisms and ecosystems in many ways. Although not every pesticide has effects on people, in the United States and most other nations, new chemical products are not thoroughly tested for health effects before being brought to market (p. 378), so a pesticide may cause health impacts yet still be widely used.

An additional problem is that pesticides commonly kill nontarget organisms, including the predators and parasites of the pests they are meant to target. When these valuable natural enemies are eliminated, pest populations become even harder to control. Moreover, as just discussed, chemical pesticides affect pollinating insects. For instance, the use of Roundup in North America has been so widespread that milkweed has gone from being abundant in and near farm fields to being scarce. Monarch butterflies rely on milkweed for food, so as Roundup has eliminated milkweed from the landscape, monarch populations have plummeted (pp. 287–288).

Today a new class of chemical insecticide has become common: **neonicotinoids.** Seed companies treat crop seed with neonicotinoids and they become systemic in the plant, dispersing throughout its tissues as it grows, and ending up in leaves, stems, flowers, fruit, and pollen. "Neonics" make a plant toxic to insects; they kill insects that feed on the plant (as intended), but also harm bees pollinating the plant and predators that eat insects that feed on the plant (unintended consequences). Neonicotinoids are also applied to plants chemically, and they may enter soil, water, and even plants that grow from treated soil, continuing to kill a diversity of organisms that pose no threat to crops.

Pests evolve resistance to pesticides

Despite the toxicity of chemical pesticides, their effectiveness tends to decline with time as pests evolve resistance to them. Recall from our discussion of natural selection (pp. 48–50) that organisms within populations vary in their traits. Because most insects, weeds, and microbes can occur in huge numbers, it is likely that a small fraction of individuals may by chance already have genes that enable them to metabolize and detoxify a given pesticide (p. 366). These individuals will survive exposure to the pesticide, whereas individuals without these genes will not (**FIGURE 10.19**).

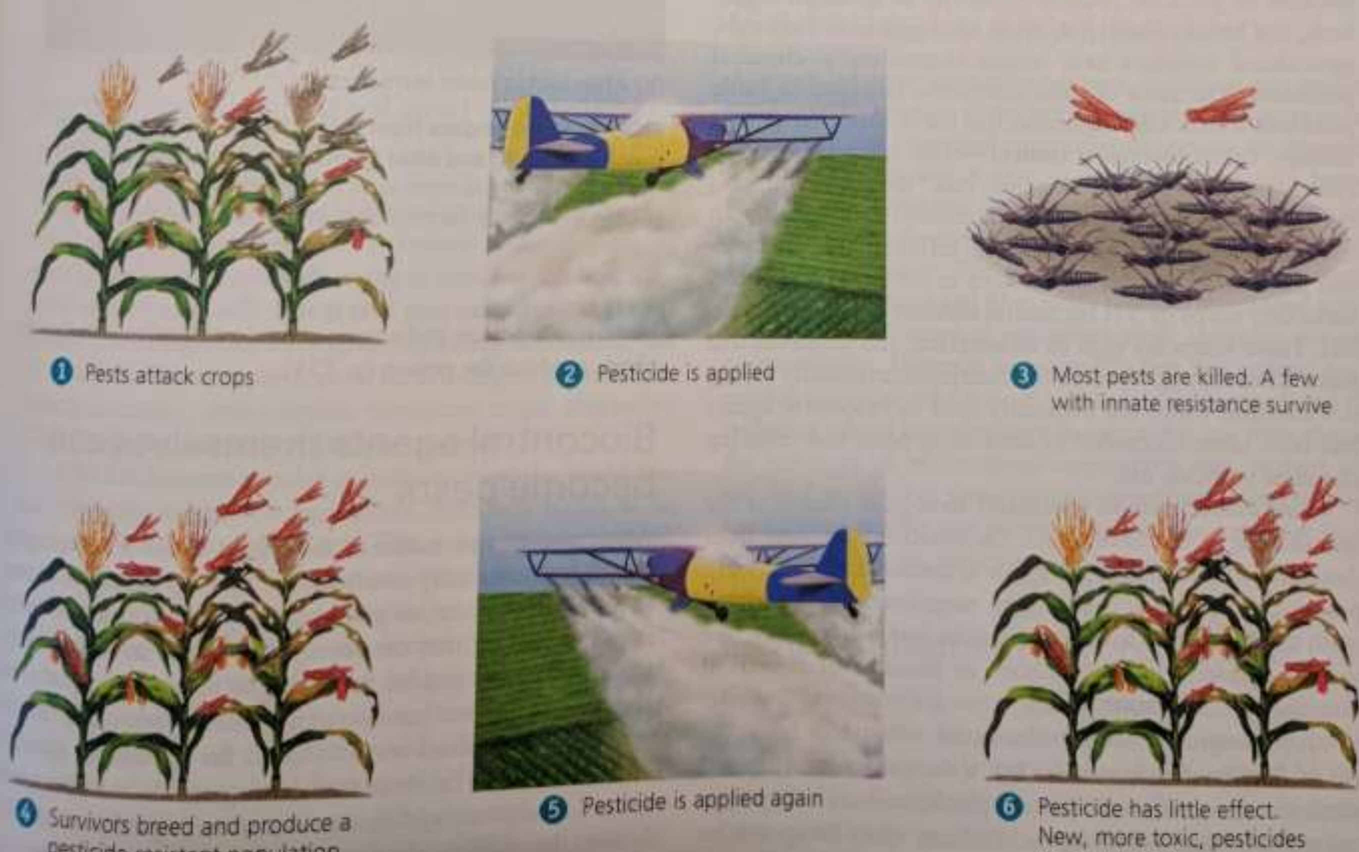


FIGURE 10.19 Through the process of natural selection, crop pests often evolve resistance to the poisons we apply to kill them.

Let's say an insecticide application kills 99.99% of the insects in a field. That sounds like a successful application, but it means that 1 in 10,000 insects survives. If an insect that is genetically resistant to an insecticide survives and mates with other resistant individuals, the genes for insecticide resistance will be passed on to their offspring. As resistant individuals become more prevalent in the pest population, insecticide applications will cease to be effective and the population will grow.

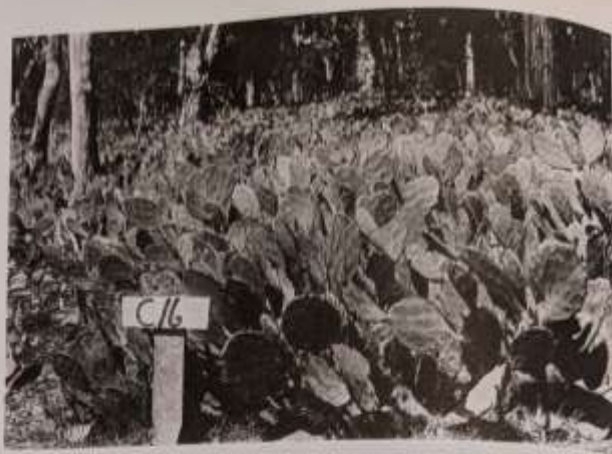
In many cases, industrial chemists are caught up in an evolutionary arms race (p. 77) with the pests they battle, racing to intensify or retarget the toxicity of their chemicals while the armies of pests evolve ever-stronger resistance to their efforts. Because we seem to be stuck in this cyclical process, it has been nicknamed the "pesticide treadmill." Today among arthropods (insects and their relatives) alone, there are more than 10,000 known cases of resistance by nearly 600 species to more than 330 insecticides. Hundreds more weed species and plant diseases have evolved resistance to herbicides and other pesticides. Many species, including insects such as the green peach aphid, Colorado potato beetle, and diamondback moth, have evolved resistance to multiple chemicals.

Biological control pits one organism against another

Because of pesticide resistance, toxicity to nontarget organisms, and human health risks from some synthetic chemicals, agricultural scientists have sought alternatives to chemical pesticides. The most obvious alternative has been to battle pests and weeds with organisms that eat or infect them. This strategy, called **biological control**—often referred to as *biocontrol*—operates on the principle that "the enemy of one's enemy is one's friend." Biological control is essentially an attempt to reestablish the restraining influence that predators and parasites exert over populations in nature. For example, parasitoid wasps (p. 77) are natural enemies of many caterpillars. These wasps lay eggs on a caterpillar, and the larvae that hatch from the eggs feed on the caterpillar, eventually killing it. Parasitoid wasps are frequently used as biocontrol agents and have often succeeded in controlling pests and reducing chemical pesticide use.

One classic case of successful biological control is the introduction of the cactus moth, *Cactoblastis cactorum*, from Argentina to Australia in the 1920s to control invasive prickly pear cactus that was overrunning rangeland. Larvae of the moth devour cactus tissue, and within just a few years, the species managed to free millions of hectares of rangeland from the cactus (FIGURE 10.20).

A widespread modern biocontrol effort has been the use of ***Bacillus thuringiensis* (Bt)**, a naturally occurring soil bacterium that produces a protein that kills many caterpillars and some fly and beetle larvae. Farmers spray Bt spores on their crops to protect against insect attack. In addition, scientists have managed to isolate the gene responsible for the bacterium's poison and engineer it into crop plants so that the plants produce the poison (p. 251).



(a) Before cactus moth introduction

(b) After cactus moth introduction

FIGURE 10.20 Photos from the 1920s show an Australian ranch before (a) and after (b) introduction of the cactus moth. Larvae of this moth were used to clear invasive non-native prickly pear cactus from millions of hectares of rangeland.

Biocontrol agents themselves can become pests

When a pest is not native to the region where it is damaging crops, scientists may consider introducing a natural enemy (a predator, parasite, or pathogen) of the pest from its native range, expecting that the enemy will attack it. Alternatively, scientists may consider importing a biocontrol agent from abroad that the pest has never encountered, reasoning that the pest has not evolved ways to avoid the biocontrol agent. In either case, this involves introducing an animal or microbe from a foreign ecosystem into a new ecological context. This is risky, because no one can know for certain what effects the biocontrol agent might have. In some cases biocontrol agents have turned invasive and become pests themselves. When this happens, biocontrol organisms are more difficult to manage than chemical controls, because they cannot be "turned off" once they are set loose.

Following the cactus moth's success in Australia, for example, the moth was introduced in other countries to control non-native prickly pear. However, moths introduced to Caribbean islands spread to Florida on their own and are now eating their way through rare native cacti in the southeastern United States. If these moths reach Mexico and the southwestern United States, they could decimate many native and economically important species of prickly pear.

In Hawai'i, wasps and flies have been introduced to control pests at least 122 times over the past century, and biologists Laurie Henneman and Jane Memmott suspected that some of these might be harming native Hawaiian caterpillars that were not pests. They sampled parasitoid wasp larvae from 2000 caterpillars of various species in a remote mountain swamp far from farmland. In this wilderness preserve, they found that fully 83% of the parasitoids were biocontrol agents that had been intended to combat lowland agricultural pests.

Because of concerns about unintended impacts, researchers study biocontrol proposals carefully before putting them into action, and government regulators must approve these efforts. If biological control works as planned, it can be a permanent, effective, and environmentally benign solution. Yet there will never be a sure-fire way of knowing in advance whether a given biocontrol program will work as planned.

Integrated pest management combines biocontrol and chemical methods

Because both biocontrol and chemical control methods pose risks, agricultural scientists and farmers began developing more sophisticated strategies, trying to combine the best attributes of each approach. **Integrated pest management (IPM)** incorporates numerous techniques, including biocontrol, use of chemicals when needed, close monitoring of populations, habitat alteration, crop rotation, transgenic crops, alternative tillage methods, and mechanical pest removal.

IPM has become popular in many parts of the world that are embracing sustainable agriculture. Indonesia stands as an exemplary case (**FIGURE 10.21**). This nation had subsidized pesticide use heavily for years but came to understand that pesticides were actually making pest problems worse. They were killing the natural enemies of the brown planthopper, which began to devastate rice fields as its populations exploded. Concluding that pesticide subsidies were costing money, causing pollution, and decreasing yields, the Indonesian government in 1986 banned the import of 57 pesticides, slashed pesticide subsidies, and promoted IPM. International experts helped teach Indonesian rice farmers about IPM, and collaborative groups of farmers traded information and experimented with new approaches. Within just 4 years, pesticide production

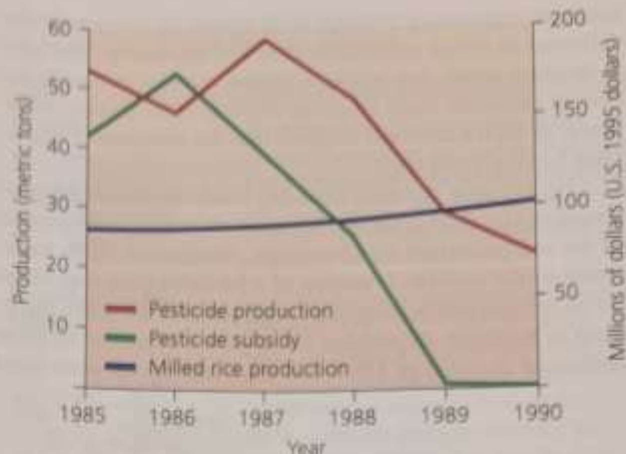


FIGURE 10.21 Once Indonesia threw its weight behind integrated pest management in 1986, pesticide production and imports were reduced, pesticide subsidies were phased out, and yields of rice increased. *Data from the World Bank.*

fell by half, pesticide imports fell by two-thirds, and subsidies were phased out (saving taxpayers $179 million annually). Rice yields rose 13%.

Genetically Modified Food

Although industrial agriculture has been feeding an ever-greater number and proportion of the world's people, relentless population growth and intensified environmental impacts are demanding further innovation. A new set of potential solutions began to arise in the 1980s and 1990s as advances in genetics enabled scientists to directly alter the genes of organisms, including crop plants and livestock. The genetic modification of organisms that provide us food and fiber holds promise to enhance nutrition and the efficiency of agriculture while lessening impacts on ecosystems. However, many people fear that genetic engineering may pose risks that are not yet fully understood, and the widening role of biotechnology in agriculture has strengthened the influence of multinational corporations over farmers and our food supply. For these reasons, agricultural biotechnology has inspired anxiety and protest among many consumer advocates, small farmers, and critics of big business.

Genetic engineering creates GMOs

Genetic engineering refers to any process whereby scientists directly manipulate an organism's genetic material in the laboratory by adding, deleting, or changing segments of DNA (pp. 27–28). **Genetically modified foods** are foods derived from **genetically modified organisms (GMOs),** organisms that are genetically engineered. Genetic engineering uses recombinant DNA (DNA patched together from the DNA of