The Habitable Planet

Unit 7 : Agriculture

Wheat Farm in Yaqui Valley, Mexico. Courtesy of Ivan Ortiz Monasterio

Overview

Demographers project that Earth's population will peak during the 21st century at approximately ten billion people. But the amount of new cultivable land that can be brought under production is limited. In many nations, the need to feed a growing population is spurring an intensification of agriculture—finding ways to grow higher yields of food, fuel, and fiber from a given amount of land, water, and labor. This unit describes the physical and environmental factors that limit crop growth and discusses ways of minimizing agriculture's extensive environmental impacts.

Sections:

1. Introduction

Agriculture is the human enterprise by which natural ecosystems are transformed into ones devoted to the production of food, fiber, and, increasingly, fuel. Given the current size of the human population, agriculture is essential. Without the enhanced production of edible biomass that characterizes agricultural systems, there would simply not be enough to eat. The land, water, and energy resources required to support this level of food production, however, are vast. Thus agriculture represents a major way in which humans impact terrestrial ecosystems.

For centuries scholars have wrestled with the question of how many people Earth can feed. In 1798 English political economist Thomas Robert Malthus published what would become one of the most famous pamphlets in social science, **An Essay on the Principle of Population**. Malthus proposed that because population tended to increase at a geometric (exponential) rate, while food supplies could only grow at an arithmetic rate, all living creatures tended to increase beyond their available resources.

"Man is necessarily confined in room," Malthus argued. "When acre has been added to acre till all fertile land is occupied, the yearly increase of food must depend upon the melioration of the land already in possession. This is a fund; which, from the nature of all soils, instead of increasing must gradually be decreasing" (footnote 1). The resulting scarcity, he predicted, would limit human population growth through both "positive checks," such as poverty, diseases, wars, and famines, and self-imposed "negative checks," including late marriage and sexual abstinence.

In terms of global food production, however, Malthus has so far been proved wrong because his essay failed to take into account the ways in which agricultural productivity of cultivated lands, measured in terms of harvested (typically edible) biomass, could be enhanced. Agriculture involves the genetic modification of plant and animal species, as well as the manipulation of resource availability and species interactions. Scientific and technological advances have made agriculture increasingly productive by augmenting the resources needed to support photosynthesis and by developing plants and animals with enhanced capacity to convert such resources into a harvestable form. The outcome is that world food production has in fact kept up with rapid population growth. Gains have been especially dramatic in the past 50 years (Fig. 1).

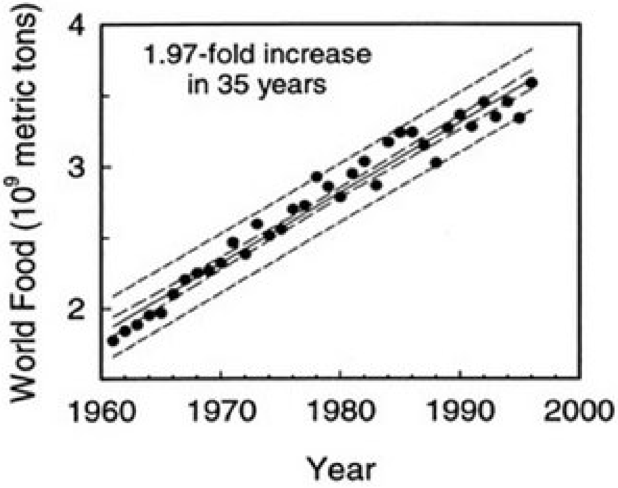

Figure 1. World food production, 1961–1996 (measured as the sum of cereals, coarse grains, and root crops)

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But these gains carry with them serious environmental costs. Large-scale agriculture has reduced biodiversity, fragmented natural ecosystems, diverted or polluted fresh water resources, and altered the nutrient balance of adjacent and downstream ecosystems. Agriculture also consumes major amounts of energy and generates greenhouse gas emissions that contribute to global climate change. However, these negative impacts must be weighed against human demand for food, as well as the fact that agriculture is the primary livelihood for 40 percent of the human population. In some countries, more than 80 percent of the population makes a livelihood from farming, so increasing agricultural productivity not only makes more food available but also increases incomes and living standards.

The future impacts of agriculture will depend on many factors, including world demand for food, the availability and cost of resources needed to support high levels of productivity, and technological advances to make agriculture more efficient. Global climate change is expected to alter temperature, precipitation, and weather patterns worldwide, thus changing many fundamental conditions that guide current agricultural practice. (For more details, see Unit 12, "Earth's Changing Climate.")

2. Earth's Land Resources

How much of Earth's surface can be used for agriculture? The basic limits are temperature, topography, climate, soil quality, and available technologies, including scientific understanding of issues like plant and animal genetics. As technology improves over time, the zone where agriculture can be practiced successfully expands. For example, development of the horse collar in China allowed farmers to use livestock to pull ploughs and thus to farm in heavier soils than they could till by hand. Many social, political, and economic factors also shape agricultural land use, including land tenure patterns, population density, and environmental regulations.

As of the year 2000, about 37 percent of Earth's land area was agricultural land. About one-third of this area, or 11 percent of Earth's total land, is used for crops. The balance, roughly one-fourth of Earth's land area, is pastureland, which includes cultivated or wild forage crops for animals and open land used for grazing (footnote 2).

To help governments with land-use planning, the United Nations Food and Agricultural Organization (FAO) has developed a system called Agro-Ecological Zoning that characterizes land's suitability for agriculture based on physical parameters like climate, soil, and topography (footnote 3). Based on current soil, terrain, and climate data, FAO estimates that more than three-quarters of Earth’s land surface is unsuitable for growing rain-fed crops (i.e., raising crops without irrigation). Most of the remainder is subject to some soil, terrain, and/or climate limitations. On average, only about 3.5 percent of Earth’s surface is suitable for agriculture without any physical constraints (Fig. 2).

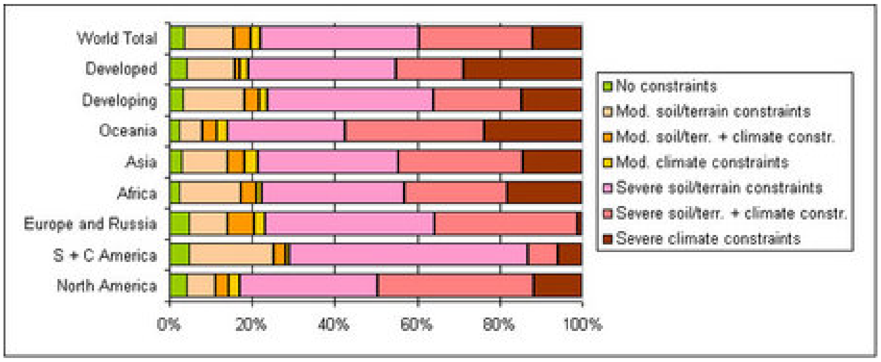

Figure 2. Distribution of climate and soil/terrain constraints by region

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These physical constraints mean that not all farmland is equally productive, even with modern techniques and inputs. In areas where land is less productive, agriculture requires more techniques and inputs to address limitations such as poor soil quality. Less productive agricultural land generally has low market value, so in many countries farming must compete with other uses such as residential or commercial development or recreation. However, in areas that have received few modern inputs, such as many parts of Africa, fertilizer and other technologies can greatly increase productivity and raise the value of agricultural land.

In regions where productivity is rising faster than demand, such as the United States, the European Union, and Japan, land is being withdrawn from cultivation. These areas rely on agricultural intensification to keep output high as their farmed lands shrink. In contrast, land is being converted for agriculture in many parts of the developing world. Both trends are causes for concern. Agricultural intensification has serious environmental impacts, as we will see in the following sections, while land conversion is a major cause of deforestation. Clearing forests for agriculture alters ecosystems that provide important services such as sequestering carbon or absorbing floodwaters.

Another 30 percent of the world's land area is forested, with half of global forests managed at least partly for wood production (other forest functions may include land conservation or protecting indigenous plants and animals) (footnote 4). Forestry is generally a much less intense form of land use than agriculture because tree crops have longer rotation periods than agricultural commodities, so soils are less disturbed and fewer cultivation inputs like fertilizer are needed. However, some forestry practices—such as building roads through forest tracts and clear-cutting on hillsides where trees stabilize soil—can disrupt ecosystems on a scale comparable to farming.

3. Key Inputs for Photosynthesis

Photosynthesis, in which plants convert and water into plant tissue, is the foundation for agricultural productivity. Before we consider how tools like plant breeding and fertilizer can increase farmers' output, we need to understand this basic process and the constraints on it, including the key roles played by water and nitrogen (N).

Drought is the biggest limit on agricultural productivity because plants need an enormous amount of water. When plants photosynthesize, they use energy from sunlight to convert carbon dioxide (CO_2) and water into carbohydrates. As discussed in Unit 4, "Ecosystems," the basic equation for photosynthesis is:

$$CO_2 + H_2O + \text{sunlight} \rightarrow (CH_2O)_n + O_2$$

From this equation it might appear that plants would need equal amounts of water and CO_2, but the actual ratio is approximately 400 to 1. Where does all of this water go? More than 98 percent of a plant's water intake passes upward through the plant from roots to leaves and evaporates, exiting the leaf as water vapor through pores in the leaf surface called stomata. Movement of water from the soil to the atmosphere through the bodies of plants is called transpiration. This process serves many important functions: it carries minerals from the soil to the leaves and prevents leaves from overheating. However, the principle reason that plants transpire is to allow uptake of CO_2 from the atmosphere.

As water diffuses out of plants' leaves into the surrounding atmosphere, CO_2 diffuses in (Fig. 3). The exchange ratio between CO_2 intake and water loss is lopsided: diffusion of water molecules out of the leaf is much greater than diffusion of CO_2 into the leaf. This happens because the outside atmosphere is much less moist than the interior of a plant: relative humidity is roughly 50 percent outside, compared to 100 percent at the center of leaves, so water diffuses easily out of plants. In contrast, the atmosphere is only about 0.037 percent CO_2, so there is a much smaller contrast between CO_2 concentrations inside and outside the leaf.

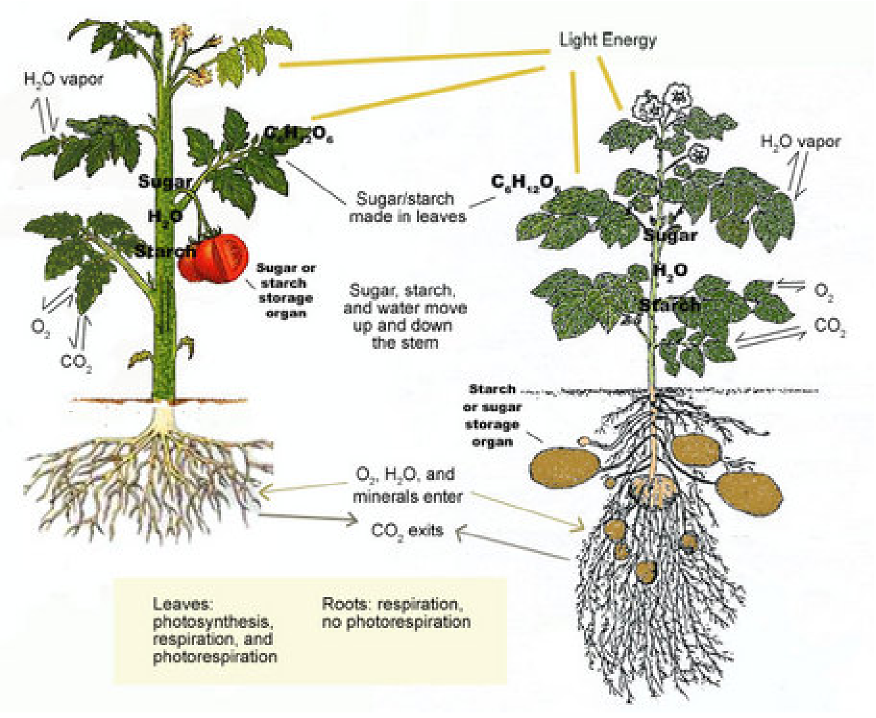

Figure 3. How plants grow

This simple relationship describing the diffusional exchange of water and CO_2 explains why drought is the major factor limiting agricultural yields worldwide. Because the atmosphere is a very dilute CO_2 source, plants need to maximize CO_2 intake as long as it will not dry out their interiors. Stomata open to promote gas exchange with the atmosphere when water is plentiful, and constrict or close when water is scarce. If stomata must close to conserve water, the plant will not have access to the CO_2 it needs to photosynthesize. Therefore, to encourage growth it is essential to supply plants with enough water.

Many farming regions rely on irrigation to increase productivity and ensure consistent yields regardless of yearly fluctuations in rainfall. One-third of global food harvests come from irrigated areas, which account for about 16 percent of total world cropland. Every year, humans divert about 2,700 cubic kilometers of water (five times the annual flow of the Mississippi River) from the global water cycle for crops. Without irrigation, some countries such as Egypt would be able to support only very limited forms of agriculture, and grain production in northern China, northwest India, and the western Great Plains of the United States would fall sharply (Fig. 4).

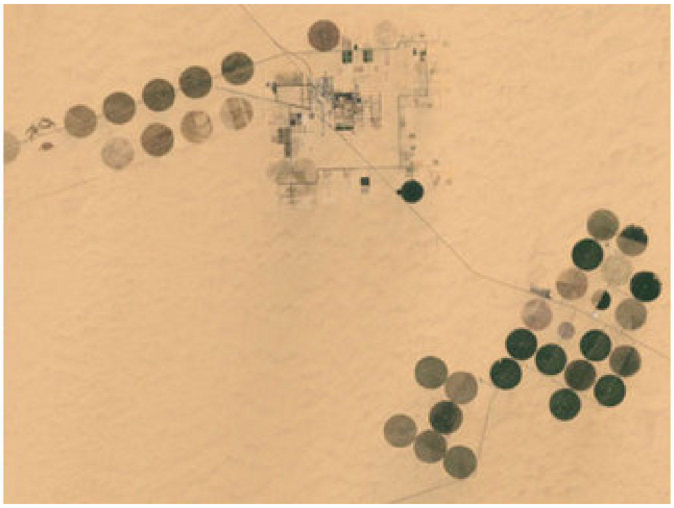

Figure 4. Irrigation in the heart of the Sahara

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Nitrogen (N), which plants obtain from the soil, is another critical resource for photosynthesis. Natural levels of N availability frequently limit crop yields. Nitrogen is an essential component of proteins, including the enzyme ribulose-bisphosphate-carboxylase-oxygenase (abbreviated as RUBISCO), which catalyzes the incorporation of CO_2 into an organic molecule. RUBISCO is thought to be the most abundant protein on Earth, with leaves typically being 2 percent (by dry weight) nitrogen. This is because RUBISCO, from a catalytic point of view, is one of the slowest enzymes known, reflecting an inherent tradeoff between catalytic efficiency (speed) and selectivity (distinguishing between CO_2 and O_2).

Before dismissing RUBISCO as inefficient (and thus easily improved upon), it is important to realize the constraints under which it operates. From RUBISCO's point of view, CO_2 and O_2 are quite similar in many ways. RUBISCO is a very large molecule, along side of which CO_2 and O_2 appear quite similar in size. Furthermore, the two are both uncharged molecules that can react in a similar manner. However, the real challenge is that the ratio of O_2 to CO_2 in Earth's atmosphere is greater than 500:1. RUBISCO thus is forced to go slowly so that it can maintain a high selectivity for CO_2. Like the diffusional uptake of CO_2, which makes photosynthesis extremely water-intensive, this tradeoff for RUBISCO between speed and selectivity means that nitrogen plays an important role in natural and agricultural ecosystems.

Prior to World War I the main source of nitrogen fertilizer was organic manure from livestock animals. Explorers also sought out mineral deposits that could be exploited. Chile derived a major share if its gross domestic product from nitrate (saltpeter) mines from roughly 1880 through World War I. Prior to the exploitation of these naturally occurring mineral deposits, guano (seabird droppings) along the coasts of Chile and Peru and on Pacific islands, where seabirds feed on fish in nutrient-rich coastal waters, were a prized source (Fig. 5). In 1856 the U.S. Congress passed the Guano Islands Act, empowering U.S. citizens to take possession of unoccupied islands anywhere in the world that contained guano deposits if the islands were not under the jurisdiction of other governments (footnote 5).

Figure 5. Guano deposits on Gardner Pinnacles, Laysan Island, Hawaii, 1969

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In 1908 German chemist Fritz Haber developed the Haber-Bosch process for combining nitrogen and hydrogen gases at high temperatures to produce ammonia (NH_3), which can be processed further into nitrate. The process was commercialized and developed on an industrial scale during World War I and World War II to make nitric acid for munitions. It also launched the fertilizer industry. Synthetic fertilizer entered widespread use after World War II, and the increased levels of nitrogen available to support plant growth boosted crop productivity in regions where farmers could afford synthetic fertilizers.

Producing nitrogen fertilizers requires substantial amounts of energy. Although Earth's atmosphere is about 80 percent nitrogen gas (N_2), the triple bond of the dinitrogen molecule is so strong that only a small number of prokaryotic organisms can make use of it. Industrial production of N fertilizers takes place at high temperatures and pressures to crack this bond. In addition, the Haber-Bosch process involves oxidizing natural gas (CH_4) over an inorganic catalyst to produce hydrogen gas.

Today nitrogen fertilizers are used on a vast scale. World nitrogen fertilizer consumption was approximately 80 million tons in 1999, with as much as 400 kilograms per hectare applied in areas of highly intensified agricultural production. To put this in perspective, the amount of atmospheric (gaseous) nitrogen incorporated in the production of synthetic fertilizers is of the same order as the amount that occurs globally through biological nitrogen fixation and lightning. In contrast, fossil fuel combustion only releases about five percent of the carbon exchange that occurs naturally through photosynthesis and respiration.

Irrigation and fertilizer help farmers ensure that crops will have the basic inputs they need to grow, but these mainstays of modern agriculture can also cause serious environmental damages. In many regions, irrigation depletes normal river flows or contributes to salinization of agricultural lands (for more information, see Unit 8, "Water Resources"). Fertilizer that is not taken up by plant roots (especially nitrogen, which is extremely mobile in its most common form, NO_3^-) can wash into nearby water bodies or into ground water, altering the species composition and nutrient balance of downstream ecosystems. This problem is most severe early in the growing season when plants are small and do not have enough root mass to keep water and nutrients from infiltrating into ground water. Mismanaged livestock manure (discussed in section 6) causes similar problems.

4. Increasing Yields

Undisturbed ecosystems maintain themselves by cycling nutrients and other inputs, like water and energy, up through food webs. As discussed in Unit 4, “Ecosystems,” these cycles are closed loops to a large extent. Substances change form as they move through ecosystems, but they are not destroyed or removed from the system.

Agriculture is fundamentally different from undisturbed ecosystems because harvesting crops removes material from the system. The product that can be harvested from an agricultural system, which is called its yield, represents a loss of materials such as water and nutrients from the system. Farmers can increase yields by adding energy and materials, by increasing the efficiency of energy conversion and allocation to the harvested product, or by reducing losses that occur during the growing process.

Agricultural yields have risen steadily throughout the history of human cultivation, with particularly steep increases throughout the 20th century. From 1961 through 1999, the FAO's aggregate crop production index increased at an average rate of 2.3 percent per year and world crop production per capita rose at an average annual rate of 0.6 percent (footnote 6). Global production of major cereal crops more than doubled during this period (Fig. 6).

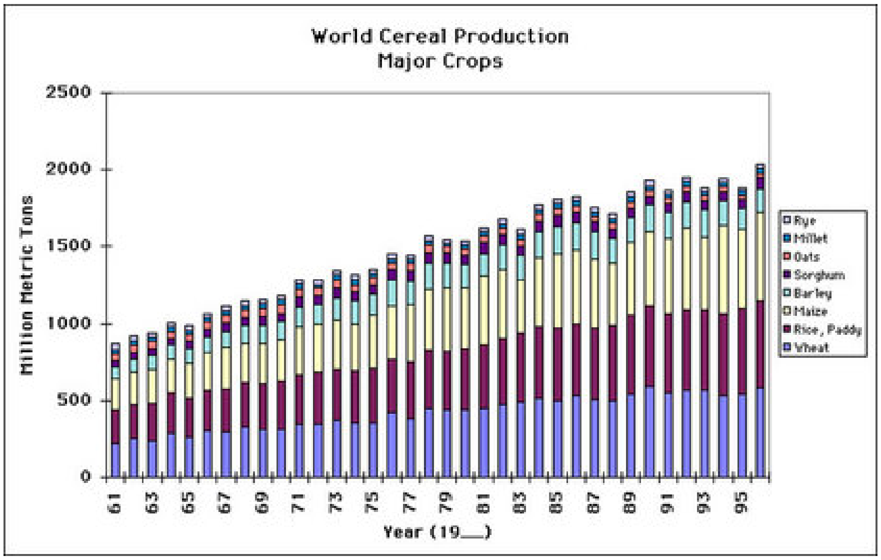

Figure 6. World cereal production

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Productivity in agriculture is a measurement of farmers' total output per unit of land. If the gains shown in Figure 6 had come simply from bringing twice as much land under cultivation, they would not automatically signal that productivity was rising as long as farmers were using the same amount of inputs per acre. However, agriculture has become much more productive over time. In many parts of the world, modern farmers get far more product from each unit of land than their predecessors thanks to intensification—using more technological inputs per acre. In areas where such inputs are not available, such as Africa, output rates remain far below world averages.

Radical changes in agricultural inputs over the past century made this increase possible. Land and labor inputs have fallen drastically in industrialized countries, but technological advances such as large-scale irrigation, synthetic fertilizers, pesticides and herbicides, and capital investment (in the form of mechanization) have increased sharply. Scientific advances such as development of higher-yielding crop varieties have also contributed to increased productivity.

The most significant way in which scientists have produced bigger yields is by modifying plants so that they devote a larger proportion of their physical structures to producing biomass that is usable for food. This process is referred to as increasing the harvest index (the ratio of harvested biomass to total biomass). For example, growing deep root systems protects wild plants against drought, but this allocation strategy limits the amount of plant biomass available to make leaves, so they have fewer sugars from photosynthesis available to make seeds. Plant breeders selecting for higher-yielding varieties might try to increase the harvest index by including plants that produce fewer roots and more seeds, or by developing dwarf or semi-dwarf strains. Figure 7 shows several modifications that have increased rice yields.

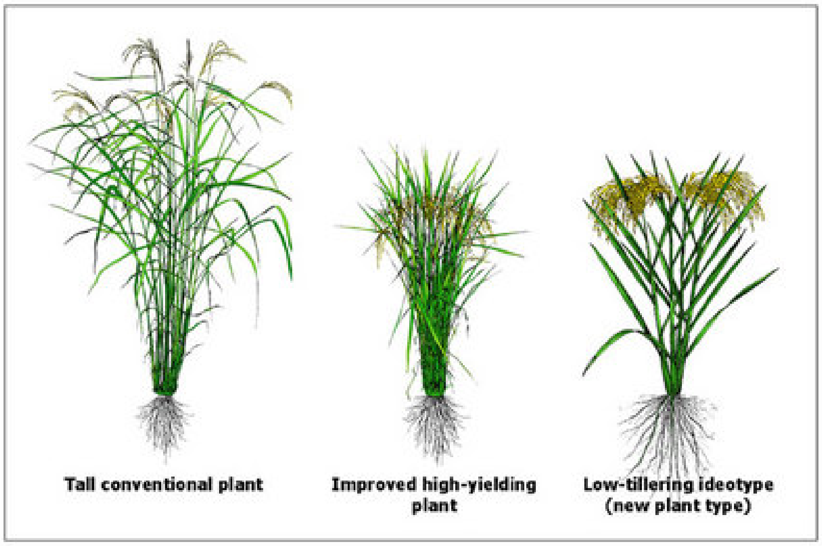

Figure 7. Rice varieties

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This approach was an important component of the "Green Revolution"—a 30-year transformation of agriculture in developing regions that started in the 1940s, when private foundations and national governments joined forces to distribute high-yielding crop varieties, synthetic fertilizer, irrigation, and pesticides to subsistence farmers in Asia and Latin America. By introducing semi-dwarf varieties of wheat and rice, researchers increased the crops' harvest indexes and reduced the problem of lodging (falling over before harvest due to excessive growth). This shift made it possible for farmers to apply higher levels of chemical fertilizers so that plants would photosynthesize at increased rates and produce more biomass. Scientists also developed these new strains to make them easier to harvest, more durable during transport, and longer-lasting in storage.

The Green Revolution helped world food production to increase at a rate faster than population growth from 1950 onward. However, these increases relied on synthetic fertilizer and irrigation because green revolution plant varieties were designed to produce high yields when supplied with high inputs of nitrogen and water. In other words, they were not inherently high-yielding plants (i.e., they were not able to use resources more efficiently than traditional varieties) and likely would have done worse under "natural" conditions. Many varieties were highly susceptible to pests and diseases, so they also required heavy use of pesticides to thrive. Because the new plants were short, they were more susceptible to competition from weeds, so farmers also had to use herbicides to raise them.

As we will see in the next section, this strategy generated further complications for human health, non-target species, and the environment in the regions where it was applied. Conversely, because Green Revolution agriculture is capital-intensive and requires well-developed infrastructure systems for functions such as delivering irrigation water, it essentially bypassed sub-Saharan Africa.

5. Combating Pests and Disease

As agriculture became increasingly dependent on technological inputs throughout the 20th century, it also underwent a structural shift, particularly in developed countries. Instead of raising a diverse mix of crops, farmers increasingly planted large holdings of one or a few crop varieties that had been developed for high yields. Monoculture makes it easier to cultivate large acreages more efficiently, especially using mechanized equipment and chemical inputs. However, these artificial ecosystems are vulnerable to outbreaks of pests and pathogens because they do not have natural protection from genetic diversity and they are typically nutrient-rich, thanks to abundant fertilizer use. Moreover, many pest species have adapted to spread rapidly in ecosystems where recent disturbances, such as plowing, have eliminated natural predators (for background, see Unit 4, "Ecosystems").

Agricultural pests include insects, mammals such as mice and rats, unwanted plants (weeds), fungi, and microorganisms such as bacteria and viruses. Humans have controlled pests with naturally-occurring substances such as salt, sulfur, and arsenic for centuries, but synthetic pesticides, first developed during World War II, are generally more effective.

Many of the first pesticides that were widely used for agriculture were organochlorines such as DDT (dichloro diphenyl trichloroethane), aldrin, dieldrin, and heptachlor. These substances are effective against a range of insects and household pests, but in the 1950s and 1960s they were shown to cause human health effects including dizziness, seizures, respiratory illness, and immune system dysfunction. Most organochlorines have been banned in the United States and other developed countries but remain in use in developing countries.

In her 1962 book **Silent Spring**, biologist and author Rachel Carson drew wide-scale public attention to the environmental effects of pesticides. Carson described how actions such as spraying elm trees with broad-spectrum pesticides to prevent Dutch elm disease severely affected many other parts of local ecosystems (Box 1).

Bioaccumulation of DDT and other organochlorines drastically reduced populations of bald eagles and other large predatory birds that fed at the top of the food chain. The pesticides disrupted birds' reproductive systems and caused them to lay eggs with very thin shells that broke before young birds hatched (Fig. 8).

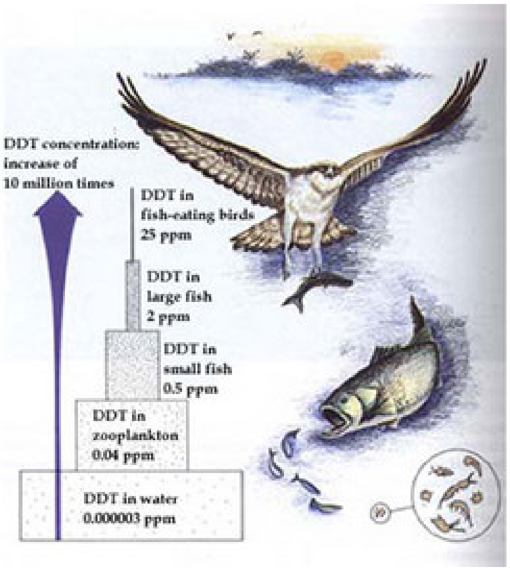

Figure 8. DDT accumulation in the food chain

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Organochlorines were replaced in the 1970s with other pesticides that were less toxic and more narrowly targeted to specific pests. However, many of these newer options still killed off pests' natural enemies, and when the insecticides were used repeatedly over time, pests became resistant to them through natural selection (many types of insects can develop through entire generations in days or weeks). Today hundreds of species of insects and weeds are resistant to major pesticides and herbicides.

In response some farmers have turned to methods such as releasing natural insect predators or breeding resistance into crops. For example, U.S. farmers can buy corn seeds that have been engineered to resist rootworms, corn borers, or both pests, depending on which are present locally, as well as corn that has been developed to tolerate herbicides. Others practice integrated pest management (IPM), an approach under which farmers consider each crop and pest problem as a whole and design a targeted program drawing on multiple control technologies, including pesticides, natural predators, and other methods.

In one notable case, Indonesia launched an IPM program in 1986 to control the brown planthopper, a notorious pest that lays its eggs inside rice plant stalks, out of range of pesticides. Outreach agents trained farmers to monitor their fields for planthoppers and their natural predators, and to treat outbreaks using minimal pesticide applications or alternative methods such as biological controls (Fig.

9). Over the following decade rice production increased by 15 percent while pesticide use fell by 60 percent. Yields on IPM lands rose from 6 to almost 7.5 tons of rice per hectare (footnote 7).

Figure 9. Gathering insects for identification during IPM training, Indonesia

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Plowing originally developed as a way to control pests (weeds), but created new issues in the process. Bare lands that have been plowed but have not yet developed crop cover are highly susceptible to erosion. The Dust Bowl that occurred in the United States in the 1930s was caused partly by poor agricultural practices. With support from the federal government, farmers plowed land that was too dry for farming across the Great Plains, destroying prairie grasses that held topsoil in place. When repeated droughts and windstorms struck the central and western states, hundreds of millions of tons of topsoil blew away. Today a similar process is taking place in northern China, where over-plowing and overgrazing are expanding the Gobi Desert and generating huge dust storms that scour Beijing and other large cities to the east.

Excessive plowing can also depress crop production by altering soil microbial communities and contributing to the breakdown of organic matter. To conserve soil carbon and reduce erosion, some farmers have turned to alternative practices such as no-till or direct-drill agriculture, in which crops are sown without cultivating the soil in advance. Direct drilling has been widely adopted in Australia, and some 17.5 percent of U.S. croplands were planted using no-till techniques as of the year 2000 (footnote 8).

No-till agriculture enhances soil development and fertility. It is usually practiced in combination with methods that leave crop residues on the field, which helps to preserve moisture, prevent erosion, and increase soil carbon pools. However, no-till requires an alternative strategy for weed control and thus frequently involves substantial use of herbicides and chemical means to control other pests.

6. Livestock: Growing Animals

Many subsistence farmers in traditional societies raise livestock along with their crops, either for their families' use or for sale. But in industrialized nations, animal agriculture has been transformed in much the same way as crop production over the past century. Modern livestock farms are large and specialized and rely heavily on technology inputs. Like major plant crops, meat and dairy products are increasingly produced through a kind of monoculture in which farmers raise one or a few animal strains that have been bred to maximize output—hens that lay more eggs, dairy cows that produce more milk, or pigs that grow quickly and develop lean meat. Producers use technological inputs, such as antibiotics and hormone treatments, to make animals grow larger and more quickly.

To maximize efficiency, large-scale livestock farms confine animals indoors instead of letting them range outside (Fig. 10). Confining animals makes it easier to control the amount and type of feed they receive, administer medications and growth supplements, and artificially inseminate breeding females. But it also generates new management issues. Crowding stresses animals and promotes disease transmission, so many livestock farmers use antibiotics not only to treat sick animals but to prevent illnesses and promote growth. Many of these drugs are identical or similar to antibiotics used in human medicine, so their overuse threatens human health by promoting the development of drug-resistant bacterial strains that can infect humans through the food chain or via direct exposure to farm animals or wastes.

In addition, large farms accumulate massive quantities of animal waste. One cow can produce more than 40 pounds of manure per day. Manure liquefies when it is washed out of barns, so it is too heavy to transport economically over long distances. Many large farms store millions of gallons of manure onsite in tanks or lagoons (which may be lined or unlined, depending on local regulations), until it can be used on neighboring fields.

Figure 10. Confined hog production facility

© United States Geological Survey, Toxic Substances Hydrology Program.

When manure leaks or spills from storage, it sends large pulses of nutrients into local water bodies, causing algal blooms that deplete dissolved oxygen in the water and kill fish when they die and decompose. Nutrient pollution also occurs when manure is applied too heavily to farmland, so that plants cannot take up all of the available nitrogen and phosphate before the manure leaches into nearby rivers and streams. Excess nutrients, mainly from agricultural runoff, are a major cause of "dead zones" in large water bodies such as the Chesapeake Bay and the Gulf of Mexico (for details, see Unit 8, "Water Resources"). Manure also pollutes water with bacteria, hormones, and other chemical residues from animal feed.

Large livestock farms also generate air pollution from manure, dust, and greenhouse gases produced in the digestive systems of cattle and sheep. Many people who live near animal feeding operations complain about smells and suffer physical symptoms such as burning eyes, sore throats, and nausea. A 2003 National Research Council study found that livestock farms produce many air pollutants that are significant hazards at scales ranging from local to global (Table 1). However, the report concluded that more analysis was required to develop accurate measurements of these emissions as a basis for regulations and that the United States lacked standards for quantifying odor, which could be caused by various combinations of hundreds of compounds (footnote 9). (For more details on emissions and health risks, see Unit 6, "Risk, Exposure, and Health"; Unit 11, "Atmospheric Pollution"; and Unit 12, "Earth's Changing Climate.")

Table 1. Potential importance of air emissions from animal feeding operations at different spatial scales.

Emission	Global, national, and regional importance	Local Importance (property line or nearest dwelling)	Primary effects of concern
Ammonia (NH3)	Major	Minor	Acid rain, haze
Nitrous oxide (N2O)	Significant	Insignificant	Global climate change
Nitrogen oxides (NOX)	Significant	Minor	Haze, acid rain, smog
Methane (CH4)	Significant	Insignificant	Global climate change
Volatile organic compounds (VOCs)	Insignificant	Minor	Quality of human life
Hydrogen sulfide (H2S)	Insignificant	Significant	Quality of human life
Particulate matter (PM10)	Insignificant	Significant	Haze
Fine particulate matter (PM2.5)	Insignificant	Significant	Health, haze
Odor	Insignificant	Major	Quality of human life

World demand for meat and dairy products is increasing, driven by population growth and rising incomes in developing countries. Because of this growth and the trend toward raising animals on large-scale farms, the FAO calls livestock farming "one of the top two or three most significant contributors to the most serious environmental problems, at every scale from local to global." According to FAO's estimates, livestock production generates 18 percent of world greenhouse gas emissions (more than the transport sector), accounts for 8 percent of world water use, and is probably the largest sectoral water pollution source (footnote 10).

With global meat and dairy production predicted to roughly double between 2000 and 2050, these environmental impacts will have to be drastically reduced just to keep agricultural pollution from worsening. And as we will see in section 8, "Agriculture and Energy," the fact that humans are eating at higher trophic levels by increasing their meat consumption makes agriculture more energy-intensive than it would be if people relied mainly on plant-based diets.

7. Genetic Improvement and Food Production

Farmers have manipulated the genetic makeup of plants and animals since the dawn of agriculture. Initially they used selective breeding to promote qualities that made breeds readily usable for agriculture, such as animals that domesticated well and plants that were easy to harvest. Next, breeders focused on varieties that could be grown outside of their native geographic range—for example, overcoming natural photoperiod requirements (the amount of daylight that plants need to flower). In the twentieth century, plant geneticists selected for traits that would allow plants to use high levels of water and nitrogen to increase yields. Similarly, animal breeders worked to increase the amount of meat or milk that various domestic animal lines produced.

Today classical agricultural breeding is a highly quantitative science that uses genetic markers (specific DNA sequences) to select for desired characteristics. This approach enables scientists to manipulate the genetic makeup of crops with substantial precision, as long as genetic variation exists for particular traits. Agricultural breeders also use biotechnology to move genes across taxonomic barriers, combining genetic material from species that would not cross-breed naturally. For example, Bt corn has been modified by inserting a gene from the bacterium **Bacillus thuringiensis** that kills harmful insects so that farmers do not need to use insecticide.

Since the mid-1990s, the U.S. Department of Agriculture has approved 63 genetically engineered (GE) crops for unrestricted sale, including strains of corn, soybeans, cotton, potatoes, wheat, canola, and papaya. Most of these crops have been developed to tolerate herbicides or resist insects or fungi, while others have been engineered for specific product qualities such as longer shelf life. Products under development include grains, field crops, fruits, vegetables, trees, and flowers designed to achieve desirable growing properties such as cold or drought resistance or efficient use of nitrogen (footnote 11). The extent to which such strategies will be able to enhance agricultural productivity, however, remains to be seen.

An alternative use of biotechnology that some supporters advocate is to develop crops with improved nutritional content to combat nutritional disorders. One widely-publicized product is golden rice, a rice variety into which several "trans" or foreign genes have been added so that the plant produces beta-carotene (vitamin A) in its grains (Fig. 11). Vitamin A deficiencies are widespread in societies that consume rice-based diets, causing thousands of cases of blindness and premature deaths among children in developing countries every year. Researchers are currently working to produce golden rice that contains the recommended daily allowance of vitamin A in a 100 to 200 gram serving, as well as to ensure the bioavailability of the beta-carotene contained within the modified rice grains. But not everyone is convinced by this approach: some experts argue that the same goals could be met more cheaply by promoting balanced, diverse diets in the target countries.

Figure 11. Conventional and golden rice

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In addition to questioning whether agricultural and nutritional goals might be more effectively met using more traditional approaches, critics have raised many concerns about GE foods, including potential harm to nearby ecosystems and the possibility that GE crops or animals will hybridize with and alter the genetic makeup of wild species. For example, over-planting Bt-resistant crops could promote increased Bt resistance among pests, while genes from GE crops could give wild plants qualities that make them more weedy and invasive. Although most of these effects will probably be benign, it is hard to predict when and where GE species could have harmful effects on surrounding ecosystems.

A 2002 National Research Council report concluded that genetically modified plants posed the same broad types of environmental risks as conventionally-produced hybrids, like the strains introduced during the Green Revolution. For example, both kinds of plants could spread into surrounding ecosystems and compete with local species. But the report noted that either type of plant could have specific traits that posed unique threats and accordingly called for case-by-case regulation of new GE strains. The committee also observed that future generations of GE plants are likely to have multiple introduced traits and forecast that these products will raise issues that cannot be predicted based on experience with early herbicide- and pest-resistant crops (footnote 12).

8. Agriculture and Energy

Agriculture consumes significant quantities of energy, especially in industrialized countries. Farmers use energy directly to heat and cool buildings, operate equipment, pump irrigation water, and transport products to market. Agriculture also consumes large quantities of fossil fuel indirectly as inputs for fertilizer (a prime ingredient of which is natural gas) and pesticides (made from petroleum and natural gas). Food processing and long-distance shipment consume additional energy.

U.S. energy use in agriculture has declined by more than 25 percent since the oil price shocks of the 1970, thanks partly to practices such as conservation tilling that require less working of soil. Changes in pesticide practices, including rapid adoption of GE crops that are resistant to insects, have lowered total use of pesticides. In addition, pesticides themselves have become much more sophisticated, so smaller quantities are required.

Nonetheless, some agricultural practices remain extremely energy-intensive—most notably, raising livestock on grain. In traditional farming systems, animals eat local forage and crop wastes that are not usable as food for humans. However, large-scale livestock farmers typically feed animals grains and other protein byproducts because the animals grow to market weight more quickly and it requires less land area than grazing, so meat production can take place closer to population centers (Fig. 12).

Raising animals on grain consumes fossil fuel as inputs for the pesticides and fertilizers needed to grow feed crops. Fattening one steer on corn to market weight can consume the equivalent of 35 gallons of oil (footnote 13). Some critics argue that this is an inefficient way to use food resources because animals convert only a fraction of the energy in their feed grain to growth (for background, see Unit 4, "Ecosystems"). According to one estimate it requires two kilograms of grain to produce one kilogram of poultry, four to make one kilogram of pork, and seven to produce a kilogram of beef (footnote 14).

Figure 12. Feedlot cattle

Other agricultural sectors could become energy resources in the coming decades. High oil and gas prices since the late 1990s have spurred worldwide interest in making liquid biofuels from plant sources such as forestry waste and fast-growing energy crops. Biofuels produce fewer atmospheric pollutants and greenhouse gases than fossil-based fuels when they are combusted, although the net effect in terms of CO_2 depends on energy use during production and subsequent processing of the crop.

Biofuels are valuable substitutes for imported oil in the transport sector because they can be used in most conventional engines with minor adjustments. They include ethanol, which is grain alcohol fermented from grain crops like corn (and soon from woody plants), and biodiesel, a natural version of diesel fuel made from oil crops such as soybean, sunflower, and rapeseed. (For more details, see Unit 10, "Energy Challenges.")

Several countries have made significant investments in biofuels. Most notably, all gasoline sold in Brazil is at least 25 percent ethanol made from local sugar cane. U.S. producers currently make about 4.5 billion gallons of ethanol per year from corn, equal to 3 percent of national gasoline consumption, with production scheduled to rise to 7.5 billion gallons per year by 2012. Most ethanol plants and fuel pumps are located in Midwestern corn-growing states.

Corn ethanol is the first type of ethanol to be commercialized in the United States because corn kernels and sugar cane juice are made up of simple carbohydrates that are easy to ferment, so the production process is relatively cheap. There is growing interest in making ethanol from the cell walls of fast-growing plants such as switchgrass and willow and poplar trees, as well as corn stalks. These feedstocks are made up of complex polymers such as cellulose, hemicellulose, and lignin, which contain more energy (Fig. 13).

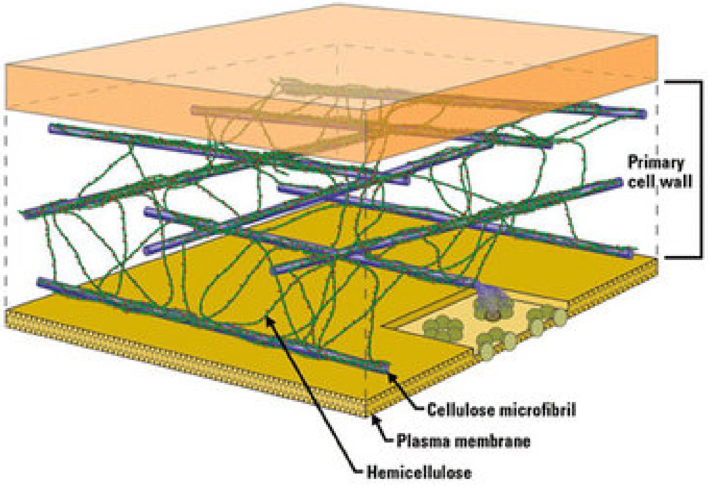

Figure 13. Simplified model of a primary cell wall

© United States Department of Energy Genome Programs/ genomics.energy.gov.

Corn ethanol has benefited U.S. farmers by increasing demand and driving up corn prices, but it only delivers modest environmental benefits. According to the U.S. Department of Energy, using corn ethanol only reduces greenhouse gas emissions by about 18 to 29 percent compared to gasoline because fertilizer and other inputs required to grow corn are made from fossil fuels. However, cellulosic ethanol could reduce greenhouse gas emissions by as much as 85 to 86 percent compared to gasoline (footnote 15).

Cellulosic plant materials are difficult to break down, and no method has been developed to date for fermenting lignin, so making cellulosic ethanol is more expensive and technically challenging than producing corn ethanol. Government agencies, universities, and private investors hope to commercialize cellulosic ethanol production in the United States as soon as 2012. If it develops into a large-scale industry, cellulosic ethanol could create new markets for farmers to grow energy crops that require fewer chemical inputs than corn and can be raised on land unsuited for food crops (Fig. 14). However, extending the footprint of agriculture in this way might also reduce biodiversity by converting more land into managed ecosystems.

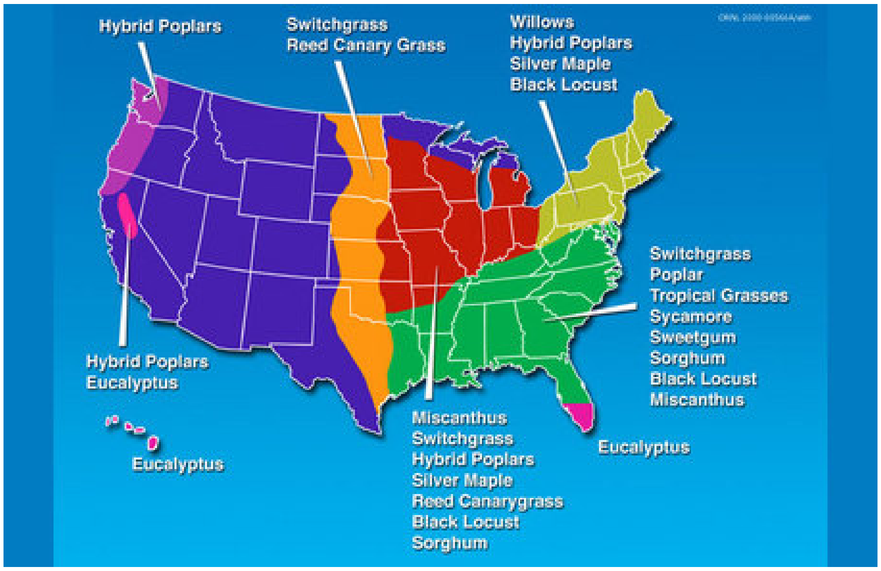

Figure 14. Geographic distribution of potential biomass energy crops

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9. Sustainable Agriculture

Growing concern about agricultural intensification in developed countries and its negative environmental impacts spurred an alternative movement in the 1970s to promote what advocates called sustainable agriculture. This perspective drew inspiration from sources that included organic farming (raising crops and animals with minimal synthetic inputs), the international environmental movement, and development advocates who criticized the Green Revolution for relying too heavily on pesticides and fertilizer. Ecology is a central pillar of sustainable agriculture, which treats farmed areas first and foremost as ecosystems, albeit unique ecosystems that have been disturbed and simplified by harvesting.

Few people would argue against the concept of sustainable agriculture, but there is no universally-agreed definition of what it means. Agricultural economist Gordon Conway describes sustainability as "the ability of an agroecosystem [an agricultural ecosystem and its social and economic setting] to maintain productivity in the face of stress or shock." Farmers use countermeasures to respond to stresses and shocks. They may draw on resources that are internal to the system, such as plants' natural pest resistance, or on outside inputs like herbicides and fertilizers.

Internal inputs typically rely on natural resources. Figure 15 shows the re-emerging practice of green manuring—tilling fresh plant material into soil to improve its physical and biological qualities. Outside inputs may be equally useful, but they usually cost more and may alter farming systems in unexpected ways—for example, introducing new species that compete with established crops (footnote 16).

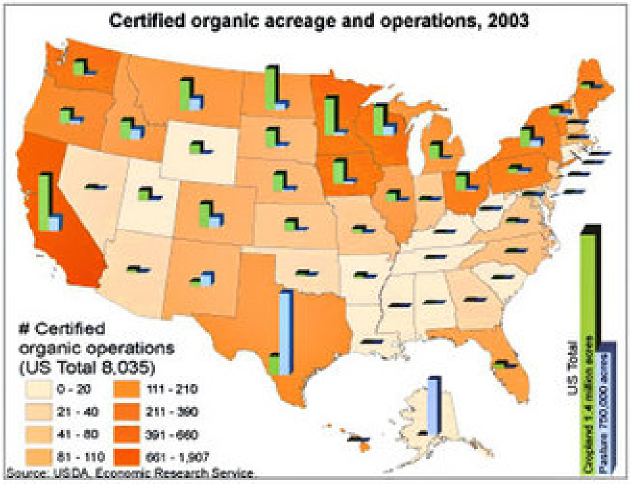
Figure 15. Chopping and disking mustard green manure, Washington state, 2003

© Washington State University Extension.

Other formulations of sustainable agriculture, including legislation passed by the U.S. Congress in 1990, present it as a compromise between several sets of social goals, including but not limited to environmental conservation. Producing enough food, fuel, and fiber to meet human needs is a major objective, along with improving environmental quality, using non-renewable resources efficiently, and ensuring that farmers can earn reasonable livings from their products (footnote 17). In terms of methods, sustainable agriculture typically stresses treating soil as an ecosystem and using methods to keep it healthy, such as retaining organic matter and preserving diverse communities of soil organisms.

Many people equate sustainable agriculture with organic farming, which is practiced according to national legal standards in more than 60 countries, including the United States, the European Union, Britain, Canada, and Australia. Generally, organic standards bar the use of synthetic pesticides, herbicides, fertilizers, and genetically modified organisms for crop production and use of antibiotics, hormones, and synthetic feeds for animals. Organic agriculture typically has less severe environmental impacts than intensive farming with synthetic inputs. On average, organic farming conserves biodiversity, improves the structure and organic content of soil, leaches less nitrate into water bodies, and produces much less pesticide pollution.

As of 2002–2003, about 4 percent of utilized agricultural land in the European Union and up to 4 percent of farmed land for certain crops in the United States was farmed organically (Fig. 16). Together, the United States and the E.U. account for 95 percent of global organic food sales.



Source: USDA, Economic Research Service.

Figure 16. U.S. certified organic acreage and operations, 2003

© United States Department of Agriculture, Economic Research Service.

Organic farming is not without its drawbacks. Output from organic farms is typically lower than from conventional agriculture for at least several years after shifting to organic production, because it takes time to restore soil productivity naturally and establish beneficial insect populations. Organic agriculture is more labor-intensive than conventional farming, so production costs are higher and farmers must receive higher prices to make a profit. And transitioning to organic production takes several years, so it is too expensive and difficult for small-scale farmers without access to technical assistance and transition funding.

With world population projected to rise from 6.5 billion in 2006 to roughly 10 billion by 2050, and growing demand for meat in developing countries (which increases demand for grain as livestock feed), world grain production may have to double in coming decades. If nations take the intensive route to this goal, using even more fertilizer, pesticides, and irrigation, nutrient pollution and freshwater depletion will increase well beyond current levels—the antithesis of sustainable agriculture (footnote 18).

One potential solution currently at the experimental stage is "precision agriculture"—using remote sensing to help farmers target fertilizer, herbicides, seeds, and water to exact locations on a field, so that resources are not over-applied or used where they are not needed. For example, satellite data could identify sectors within large cultivated fields that needed additional water or fertilizer and communicate the information to farmers driving machinery equipped with global positioning system receivers (reducing the need to apply inputs uniformly across entire fields) (footnote 19).

More broadly, agriculture will have to become more efficient in order to double world grain production without further degrading the environment. No single innovation will provide a complete solution. Rather, feeding the world sustainably is likely to require a combination of many technological inputs and sustainable techniques.

10. Food for the Future

Although the world produces enough total calories to feed all of its inhabitants today, more than 800 million people are undernourished, mainly in Africa and Asia (footnote 20). Food insecurity can have many causes, including poverty, wars, and diseases such as HIV/AIDS. However, in some areas soils and water supplies are so degraded that agricultural systems cannot produce enough food to meet human needs.

As the human population climbs towards its estimated peak of 10 billion, the environmental impacts of feeding so many people will increase. But this challenge also offers an opportunity: by making agriculture increasingly sustainable, we can meet the goal of feeding the world's population while reducing associated environmental problems such as water pollution. Reorienting agricultural systems is a complex task because the technical challenges are intertwined with social and economic issues such as land tenure and availability of foreign aid for developing countries. The magnitude of future agricultural effects on the environment will be influenced by many factors, including:

- **Actual demand for food.** Food demand will increase with population growth and rising income, which increases consumers' preference for animal protein.
- **Expansion of agricultural lands.** Agriculture will move into increasingly marginal areas because Earth's most fertile zones are already under cultivation, and will compete with other land uses such as urbanization.

- **Opportunities for increased yields.** Likely technological innovations include systems that increase availability of water and fertilizer; improved pesticides and biocontrols such as IPM; better soil conservation and management of microbial communities; and new crops that deliver increased yields under wider ranges of conditions and need fewer inputs than current strains.

- **Availability of water and chemical fertilizers.** The prices of these inputs are strongly affected by energy costs and competition for fresh water with other human activities.

- **Global climate change.** Variable weather is a major challenge for farmers because optimizing for high yields becomes more difficult as the range of potential weather conditions that might occur in any season increases. In the coming decades, global climate change is predicted to alter temperature and precipitation patterns in ways that could modify major elements of Earth's climate system (for details, see Unit 12, "Earth's Changing Climate").

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Glossary

biodiesel : A diesel-equivalent, processed fuel derived from biological sources (such as vegetable oils), that can be used in unmodified diesel-engine vehicles.

biofuel : Derived from biomass — recently living organisms or their metabolic byproducts, such as manure from cows.

ethanol : A flammable, colorless, slightly toxic chemical compound with a distinctive perfume-like odor. Also known as ethyl alcohol, drinking alcohol, or grain alcohol, in common usage it is often referred to simply as alcohol.

harvest index : The ratio of grain weight to total plant weight.

integrated pest management (IPM) : The use of a combination of the following to limit pest damage to agricultural crops: (1) agricultural practices (2) biological control agents (3) introduction of large numbers of sterile male insects (4) timed application of synthetic chemical pesticides and (5) application of pheromones and juvenile hormones.

monoculture : The growing of a single plant species over a large area.

organic agriculture/farming : A form of agriculture which avoids or largely excludes the use of synthetic fertilizers and pesticides, plant growth regulators, and livestock feed additives.

organochlorines : An organic compound containing at least one covalently bonded chlorine atom.

photosynthesis : A process in green plants and some bacteria during which light energy is absorbed by chorophyll-containing molecules and converted to chemical energy (the light reaction). During the process, carbon dioxide is reduced and combined with other chemical elements to provide the organic intermediates that form plant biomass (the dark reaction). Green plants release molecular oxygen (02), which they derive from water during the light reaction.

selective breeding : The process of developing a cultivated breed over time.

stomata : Tiny openings or pores, found mostly on the under-surface (epidermis) of a plant leaf, and used for gas exchange.

transpiration : The evaporation of water from aerial parts of plants, especially leaves but also stems, flowers, and fruits.