5 Manipulating Ecosystems for Agriculture

ECOSYSTEMS

An ecosystem is a network of energy and mineral flows in which the major functional components are populations of plants, animals, and microbes. These organisms live and perform different specialized functions in the system: plants are generally producers; animals, consumers; and microorganisms, decomposers. In each role, organisms carry out two basic tasks: (1) fixing and utilizing solar energy and (2) conserving and recycling mineral resources (Figure 5.1).

The collection of solar energy needed to power the entire ecosystem depends directly on plants. Plants themselves depend on solar energy to meet their own energy needs. Of the total energy collected, they use about 25% for respiration, 35% for building and maintaining structure, and 35% for reproduction (Figure 5.2). Plants also produce a small surplus of energy that is used by consumers. Some animals and microorganisms feed directly upon the plant population, but others obtain their energy by feeding on first-order consumers. A relatively small amount of energy—between 5% and 10%—moves from one level to the next in the food chain (Pimentel, 1988).

When plants or the animals that feed on them die, decomposers obtain their share of the energy originally fixed by the plant population. Decomposer populations consist mainly of bacteria, fungi, protozoa, arthropods, and earthworms. Some invertebrate populations feed directly on the decaying organic matter, whereas others, such as dipteran larvae, feed on decomposer microorganisms.

Decomposers are essential in the ecosystem because they help conserve mineral resources and cycle these essential elements back into the system for reuse. If the decomposers were unable to recycle the vital elements, the collection and conversion of energy into plant biomass would be limited and eventually cease. A shortage of any one essential element—nitrogen, phosphorus, potassium, calcium, sulfur—can limit or prevent the normal function of the entire ecosystem (Figure 5.1).

A given ecosystem comprises several thousand species of plants, animals, and microorganisms. The actual number of species in the ecosystem network depends on its boundaries and its physical environment. The interactions among and between organisms of the system help regulate and stabilize energy and mineral flows within complex ecosystems. Further, different ecosystems are interdependent; that is, energy and minerals frequently flow from one ecosystem to another.

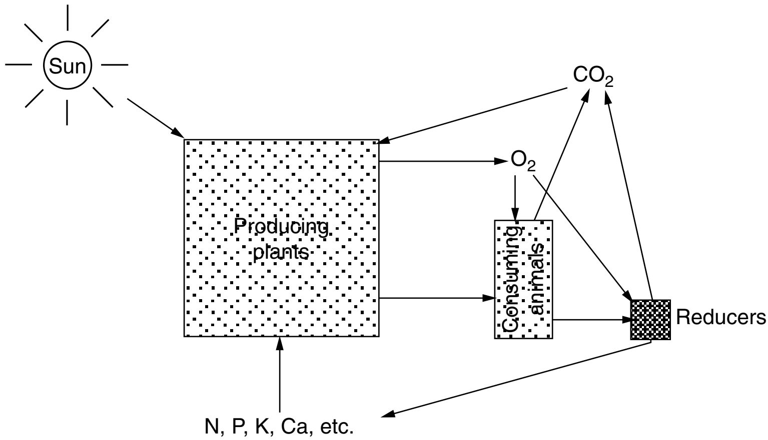

FIGURE 5.1 Producing plant-fixed solar energy that is consumed by animals, and that are in turn consumed by the reducers. The quantity of energy transferred is schematically diagrammed. Recycling of some of the mineral resources is illustrated.

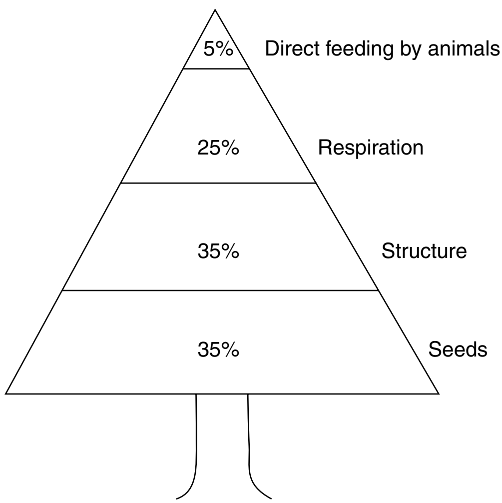

FIGURE 5.2 Of the solar energy fixed by crop plants, about 25% is used for respiration, 35% for building and maintaining the plant structure, and 35% for reproduction (seeds). The energy removed by direct feeding is estimated to be about 5%.

AGRICULTURE AND THE NATURAL ECOSYSTEM

Neither humans, their crops, nor their livestock can exist independently from species in the natural ecosystem. A relatively small number of species—about 15 major crops and 8 major livestock types—are agriculturally produced in the world. By comparison, an estimated 750,000 species of wild plants, animals, and microbes exist in the United States alone. A majority of these wild species are necessary for maintenance of the life system. At present, no one knows how many of the 750,000 species in the U.S. ecosystem can be reduced or eliminated before human life is jeopardized. Therefore, the existing biological diversity should be preserved and treasured. Environmental degradation caused by chemical pollutants, construction, deforestation, and other factors should be prevented.

Terrestrial and aquatic plants, including agricultural and forestry plants, not only convert sunlight into biomass energy but also remove carbon dioxide from the atmosphere, a benefit in the prevention of global warming and climate change. Plants also renew the oxygen supply and help clean the atmosphere of chemical pollutants.

Oxygen and ozone prevent a large percentage of the sun's ultraviolet light from reaching the Earth and thereby protect plants and animals from injury and death. No terrestrial life could exist on our planet without the ozone shield. A small increase in the amount of ultraviolet light reaching the Earth could have serious environmental effects, such as increased genetic mutations. The excessive release of chlorofluorocarbons (CFCs) into the atmosphere has significantly reduced the ozone layer, allowing more ultraviolet light to reach the Earth and increasing the incidence of cancer and eye problems. Nitrogen fertilizers also damage the ozone layer when they volatilize.

Many species in the natural ecosystem play a vital role in the breakdown of wastes produced by humans, agriculture, and wild species. Americans produce about 120 million tons of organic waste annually, and their livestock produce another 1.6 billion tons. Clearly, humans would be buried in wastes were it not for the efficient decomposing organisms of the natural ecosystem. Bacteria, fungi, protozoa, arthropods, and earthworms all help degrade wastes. These decomposing organisms also recycle essential minerals for reuse by all members of the ecosystem.

Some organisms, such as earthworms, arthropods, and microbes, improve soil structure and help create new soil by decomposing organic wastes. For example, it is estimated that earthworms bring to the surface 2.5 to 63 tons of soil castings per hectare per year (Burges and Raw, 1967). Ants may carry an additional 10 tons to the surface (Kevan, 1962).

Other species make possible the pollination of domestic and natural plants to ensure fruit and seed production. In the United States, honeybees and wild bees pollinate crops valued at about $40 billion each year. Bees and other animals are also vital in the pollination of natural vegetation.

The total number of honeybee colonies in New York state is estimated to be 125,000, with about 10,000 bees per colony. Wild bees, however, pollinate more than half of the blossoms and are vital to the success of seed and fruit production. An individual honeybee may visit 1000 blossoms on a bright sunny day, making about 10 trips and visiting about 100 blossoms on each trip. In New York state, more than 2.5×10^{12} blossoms may be pollinated in a single day by honeybees and wild bees combined.

BIOMASS

Overall, humans and their agricultural system represent but a small percentage of the Earth's total biomass. Human biomass in the United States averages about 20 kg/ha; U.S. livestock averages 100 kg/ha, outweighing the human population by more than five times.

Crops in the United States contribute slightly more than 20% of the total plant biomass produced annually. If all U.S. crops, pastures, and commercial forests were combined, the total would represent about 50% of the total vegetation biomass produced. Microbes are also important contributors. In rich productive soil, fungi and bacteria populations may total 4000 to 5000 kg/ha (wet).

Certain natural animal populations are abundant in favorable habitats. For example, earthworm populations may weigh up to 1500 kg/ha and arthropod populations may weigh about 1000 kg/ha. Therefore, compared on a weight basis with humans and their livestock, the natural biota in the ecosystem significantly dominate in biomass.

MANIPULATING AGROECOSYSTEMS

One of the earliest views of the relationship of humans to their ecosystem is found in Genesis 1:28, which says "Be fruitful, and multiply, and replenish the Earth, and subdue it." The implication seems clear that humans, by employing their energies, should overcome nature. The verse was prophetic; humans have been "fruitful" and are well on their way to overpopulating the Earth, threatening the very environment and biodiversity they depend on.

But it was more than mere population numbers that helped humans to subdue nature. The development of tools and machines, coupled with the discovery of new sources of power, especially those based on fossil energy, has enabled humans to exert tremendous control over the environment. As Forbes (1968) pointed out, science and technology are products of the "interaction between man and environment, based on the wide range of real or imagined needs and desires which guided man in his conquest of Nature."

In light of the exponential growth of the human population and the ability of new technologies to alter natural ecosystems, the solemn judgment of Dennis Gabor of the Imperial College of Science and Technology, London, is pertinent: "[E]xponential curves grow to infinity only in mathematics. In the physical world they either turn around and saturate, or they break down cata-strophically. It is our duty as thinking men to do our best towards a gentle saturation instead of sustaining exponential growth, though this faces us with very unfamiliar and distasteful problems" (in Forbes, 1968). Evidence of the extensive alteration of the ecosystem by humans, their unrestrained use of energy, land, water, and biological resources, and uncontrolled population growth substantiate Gabor's view.

Human alteration of the natural ecosystem and use of energy to manage agricultural ecosystems directly affect food production. At this point it is helpful to examine the basic characteristics of ecosystems and then, in turn, to see how these characteristics are related to ecosystem management.

As ecosystems mature, or climax, they become more complex and contain a wide variety of plant, animal, and microbe species. Their increased diversity directly contributes to their stability. When natural ecosystems are disturbed, the numbers of species are reduced, and the system becomes relatively simple. After such an alteration, "successional change" begins, and the ecosystem slowly accumulates additional species. Gradually, a new complex and relatively stable ecosystem evolves. As it becomes more complex, an ecosystem captures and circulates increasing quantities of solar energy. More energy must be expended to alter a complex ecosystem than to alter a simple ecosystem. Of course, the quantity of energy needed to alter an ecosystem depends upon the extent of the changes. Clearly, less energy is required to change the numbers of one or two species in the ecosystem than to reduce an entire ecosystem to a pure monoculture of a single species.

For instance, when an ecosystem is altered for hay production, the natural vegetation has to be destroyed; the soil is tilled, limed, and fertilized; and the hay seed is sowed. Large inputs of energy are necessary to make this alteration, whether it is done by human power or by fuel-powered machinery. Changing an ecosystem to a row crop monoculture such as Brussels sprouts or corn requires even larger inputs of energy than changing to hay production. For this kind of modification, not only are energy inputs required to destroy the natural vegetation, but additional energy inputs are needed during the growing season to prevent the invasion of weeds and other pests.

Weeds, early successional plant species in nature, will quickly invade a newly planted Brussels sprout or corn field. The invading weeds must be uprooted, buried, or chemically destroyed, requiring energy expenditures. In spite of the technology available today, it is impossible to exterminate all weeds completely. Even if it were technically possible, it would be economically and energetically impractical. In addition to weeds, insect pests and plant pathogens may invade the crop monoculture. The control of these pests, whether accomplished by cultural, environmental, or chemical methods, requires substantial energy input.

In summary, natural ecosystems possess certain patterns of species interaction and development. Altering or changing the species structure of an ecosystem, especially converting it to a monoculture, requires relatively large energy expenditures. The amount of energy invested depends on the crop, growing season, and other aspects of the environment.

INTERDEPENDENCY OF FACTORS IN CROP PRODUCTION

In the management and manipulation of agroecosystems, land, water, labor, and energy can be substituted for one another, within limits. The possibility of substituting any one of these factors for another provides some flexibility in the utilization and management of these resources.

In certain areas, for example, crops on 1 ha of high-quality land will yield as much as those grown on 2 ha of poorer quality land. However, the application of fertilizers and other energy inputs, including labor, may improve the poorer quality land to make it as productive as the high-quality land. Thus, land quality, as one factor in crop production, is dependent on available supplies of water, labor, and energy.

The impact of soil quality on crop yields and energy use is well illustrated by the environmental problem of soil erosion. In fertile agricultural land, top-soil depth usually averages 18 to 20 cm. Each 2.5 cm of topsoil lost from the land results in an average yield reduction of 250 kg/ha of corn, 161 kg/ha of wheat, 168 kg/ha of oats, or 175 kg/ha of soybeans (Pimentel et al., 1976). Although the reduced productivity of the eroded land can be offset by the use of more fertilizer and other inputs, all these interventions require considerable energy expenditures. About one-third of the topsoil from U.S. agricultural land already has been lost. An estimated 46 L/ha of fossil energy are expended in the form of fertilizers and other inputs just to maintain the productivity of the eroded land.

More important than the loss of soil depth is the loss of water, nutrients, organic matter, and soil biota due to erosion. These losses may reduce crop yields from 15% to 30% during the growing season (Follett and Stewart, 1985).

Availability of water often influences the energy inputs and the amount of land needed for the desired crop production. With ample moisture and heavy fertilizer use, crop plants can be grown densely, and high yields result. With limited moisture, however, fewer crop plants can be grown per hectare, less fertilizer can be applied, and crop yields decline.

In some regions, such as the wheat-growing section of the state of Washington, lack of moisture requires farmers to let fields lie fallow for a season before being replanted. During the fallow year, the land collects and stores sufficient moisture to support a wheat crop the next year. In such an area, overall wheat production is low compared with locations where there is ample moisture.

Irrigation is a common method of making arid land more productive. Unfortunately, pumping and applying the water over large areas requires enormous energy inputs. Therefore, water supply must be considered another interdependent factor in crop production, along with energy, land, and labor.

Labor is the final element in the agricultural equation. Human power can be substituted for machinery power in crop production, though sometimes with little

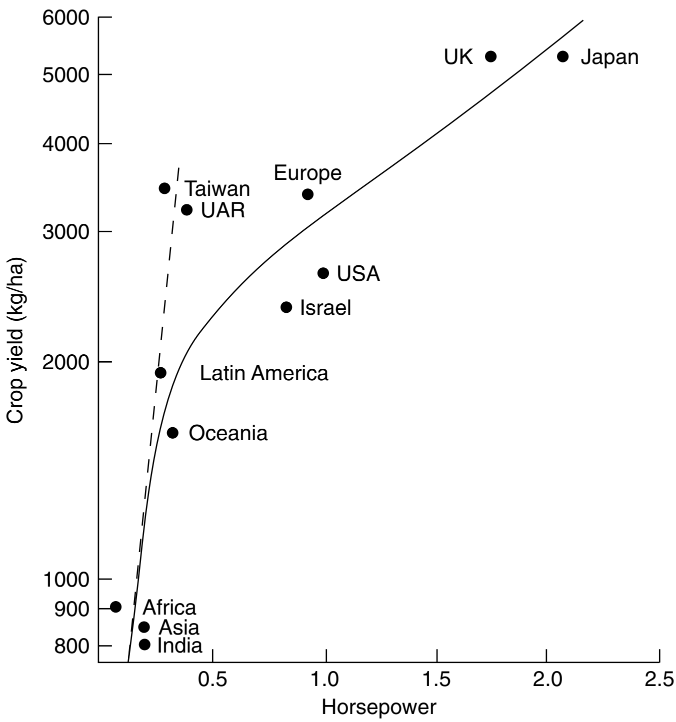

FIGURE 5.3 Relationship between crop yields per hectare of cereals, pulses, oil-seeds, sugar crops, potatoes, cassava, onions, and tomatoes, on the one hand, and horsepower per hectare, on the other, in various countries and regions (Asia excludes China). (From Blaxter, K., *Farmer's Weekly*, January 20, 1978.)

or no effect on yield. For example, a large portion of the agricultural work in India, Africa, Asia, Oceania, Latin America, and other developing countries is performed by human labor. By contrast, in the United States, Europe, and other developed countries, agriculture is heavily mechanized (Figure 5.3). Note that high crop yields are achieved in Taiwan and the United Arab Republic with minimal tractor power.

ENERGY, LABOR, AND A STANDARD OF LIVING

All operations required in agriculture can be carried out by human power. However, producing crops by hand requires about 1200 h/ha, and each person can manage only 1 ha during the growing season. Under such production conditions, only the bare minimum of essential human needs can be attained; the amount of the surplus (the crop yield not needed to feed the farmer's family) is extremely small. Only the surplus can be traded for other goods and services. For this reason, the standard of living achieved in most societies powered by human labor is relatively low compared with that possible when mechanization and large inputs of fossil fuel are used.

The definition of "standard of living" is based on the availability of goods and services, including food, clothing, housing, transportation, and health care. However, an ample supply of these things cannot and should not be equated with a high quality of life.

Fossil energy can replace large amounts of human labor, and the availability of relatively cheap supplies of fossil energy is a major reason the United States and other developed nations enjoy a high standard of living. For example, a gallon (3.79 L) of gasoline sells for slightly more than $3.00 in the United States. Based on a minimum wage of $5.25 per hour, this gallon could be purchased with slightly more than 36 min of work. However, that gallon of gasoline in an engine will produce the equivalent of 97 h of manpower. One hour of labor at $7.00 per hour would purchase the fossil fuel equivalent of about 200 h of manpower.

The relative cost of gasoline and human labor affect the price of food. If fossil energy is cheap relative to the price of food, then fossil energy use in food production is an excellent investment. In the United States today, 1000 kcal of sweet corn in a can sells for about $1.00, whereas 1000 kcal of gasoline sells for only about $0.09. Hence, 1 kcal of sweet corn is worth 10 times more than 1 kcal of gasoline energy.

The relationship of energy expenditure and standard of living also can be clarified by comparing production of corn by labor-intensive and energy-intensive systems. In Mexico, for instance, about 1144 h of human labor are required to produce 1 ha of corn by hand (Lewis, 1951). In the United States, under an energy-intensive system, only 10 h of labor are expended per hectare. In the midwestern United States, one farmer can manage up to 200 ha of corn with the help of large fossil fuel inputs and mechanized equipment. The same farmer producing corn by hand could manage 1.5 ha at most. Assuming the same profit per hectare for each farmer, it is clear that the farmer managing 200 ha will be able to support a higher standard of living.

Liberal supplies of fossil energy have helped humans to manipulate ecosystems more effectively and efficiently for food production than ever before, and this has contributed directly to improving the standard of living in many parts of the world.

REFERENCES

Blaxter, K. 1978. What happens to farming when the fossil fuels run out? *Farmer's Weekly*, January 20.

Burges, A. and F. Raw (eds.). 1967. *Soil Biology*. London: Academic Press.

Follett, R.F. and B.A. Stewart (eds.). 1985. *Soil Erosion and Crop Productivity*. Madison, WI: American Society of Agronomy, Crop Science Society of America.

Forbes, R.J. 1968. *The Conquest of Nature*. New York: Frederick Praeger.

Kevan, D.K. McE. 1962. *Soil Animals*. New York: Philosophical Library.

Lewis, O. 1951. *Life in a Mexican Village: Tepostlan Restudied*. Urbana, IL: University of Illinois Press.

Pimentel, D. 1988. Herbivore population feeding pressure on plant host: Feedback evolution and host conservation. *Oikos* 53: 289–302.

Pimentel, D., E.C. Terhune, E.C. Dyson-Hudson, et al. 1976. Land degradation: Effects on food and energy resources. *Science* 194: 149–155.