4 Ecological Systems, Natural Resources, and Food Supplies

All basic human needs, including food, energy, shelter, and protection from disease, are fulfilled using the resources found in the ecosystem. Throughout history, humans learned to modify natural ecosystems to better meet their basic needs and desires. Over time, humans have altered ever larger amounts of the environment and used ever more resources.

Human intelligence and technology have developed rapidly, enabling humans to manipulate the ecosystem more successfully than any other animal species. This advantage has given humans power to control and destroy other species. And now, with nuclear weapons, humans have the power to destroy themselves and many other species.

Humans are but one of many species on Earth; they form an integral part of the planet's ecosystems. They cannot function in isolation. Furthermore, their numbers cannot grow exponentially forever, because shortages of food, energy, and space will limit the size of the human population eventually, as has occurred for many other species in the past.

In this chapter, the intrinsic dynamics of natural ecosystems—involving land, water, atmosphere, energy, plants, and animals—are examined. The interaction of these components and their relationship to agricultural productivity are discussed.

THE STRUCTURE AND FUNCTION OF 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 perform different specialized functions in the system.

All self-sufficient ecosystems consist of producers (plants), consumers (animals and microbes), and reducers, or decomposers (animals and microbes) (see Figure 4.1). Plants collect solar energy and convert it into chemical energy via photosynthesis. They use this energy for growth, maintenance, and reproduction. In turn, plants serve as the primary energy source for all other living organisms in the ecosystem. Animals and microbes consume plants and other animals, and decomposers break down dead plants and animals and thus recycle chemical elements (carbon, hydrogen, oxygen, nitrogen, phosphorus, potassium, calcium, etc.). Through this process, the elements in the biological system are conserved and reused. Therefore, the components of

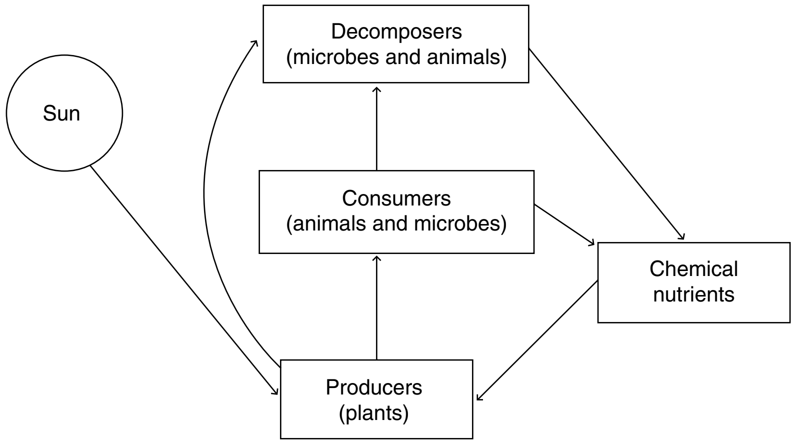

FIGURE 4.1 Structure of living systems.

the ecosystem are all interconnected and interdependent, but plants are the basic foundation of the system.

The exact number of species needed for a particular self-sufficient ecosystem depends upon many physical and chemical factors, including temperature, moisture, and the particular species present. We cannot predict how many and what kinds of species are necessary for the different feeding levels in the ecosystem. For a given ecosystem, species numbers may range from hundreds to thousands (Andrewartha and Birch, 1954).

In the United States, approximately 750,000 species of plants and animals are vital to the well-being of the natural environment. No one knows how many of these species can be eliminated before the quality of the ecosystem is diminished. Therefore, human societies must exercise great care to avoid causing a reduction in biodiversity. A delicate balance in the natural food system has evolved in each community, and, although there is some redundancy, the linkages in the trophic structure are basic to the functioning of the system.

Elton (1927) pointed out that the "whole structure and activities of the community are dependent upon questions of food supply." Plants are nurtured by the sun and by the essential chemicals they obtain from the atmosphere, soil, and water. The remainder of the species in the ecosystem depend on living or dead plants and animals. About half of all species obtain their resources directly from living hosts (Pimentel, 1968; Price, 1975). Sugarcane, for example, supports 1645 parasitic insect species worldwide (Strong et al., 1977) and at least 100 parasitic and disease microbial species (Martin et al., 1961) worldwide. Oaks in the United States support over 500 known insect species and close to 1000 different species (Packard, 1890; de Mesa, 1928; Opler, 1974). One of the major insect herbivores of oaks in the Northeast is the gypsy moth, which in turn has about 100 parasitic and predaceous species feeding on it (Nichols, 1961; Campbell and Podgwaite, 1971; Podgwaite and Campbell, 1972; Campbell, 1974; Leonard, 1974). Clearly, parasitism and dependence on living food resources constitute a dominant way of life in natural ecosystems.

But a host population can support only a limited population of herbivores before it dies or is so damaged that it no longer can provide food for its parasites. An individual host utilizes most of its energy resources for its own growth, maintenance, and reproduction. For example, on average plants use 38–71% of their energy resources for respiration; poikilotherms about 50%; and homeotherms 62–75% (McNeil and Lawton, 1970; Odum, 1971; Humphreys, 1979). In general, less than 10% of the host's resources are passed on to herbivores and other parasitic species (Slobodkin, 1960; Phillipson, 1966; Odum, 1978; Pimentel, 1988). A recent survey of 92 herbivores feeding in nature showed that they consumed only 7% of the plant host's biomass (Pimentel, 1988). Because hosts utilize most of their energy resources for themselves and their progeny, even a relatively small amount of herbivore/parasite feeding pressure influences the abundance and distribution of hosts. Therefore, from an ecological perspective, host conservation is vital for herbivore/parasite survival.

Many theories exist on how plants survive the attack of herbivore/parasite populations. It is my view that herbivore/parasite populations and plant populations coevolve and function interdependently to balance the supply and demand of food. I have proposed that parasites and hosts are dynamic participants in this economy and that control of herbivore/parasite populations generally changes from density-dependent competition and patchiness to the density-dependent genetic feedback and natural enemy (parasite feeding on parasite) controls (Pimentel, 1988). I also postulate that herbivore and parasite numbers are often controlled by a feedback evolutionary mechanism interdependent with the other density-dependent controls. Feedback evolution limits herbivore/parasite feeding pressure on the host population to some level of "harvestable" energy and conserves the host primarily by individual selection. Most of the host's resources are necessary for growth, maintenance, and reproduction, leaving a relatively small portion of host resources as harvestable energy. This hypothesis suggests one reason why trees and other plants generally remain green and lush and why herbivores and other parasites are relatively sparse in biomass, especially related to their food hosts.

To achieve a balanced economy in parasite–host systems, either individual hosts evolve defense mechanisms or herbivore/parasite populations evolve to moderate exploitation of their host population (Pimentel, 1961; Levin and Pimentel, 1981). The amount of resources consumed by herbivores/parasites is often limited to less than 10% of the host's total resources (Pimentel, 1988). Hosts' defenses include nutritional, chemical, and physical resistance and combinations of these factors (Pimentel, 1968; Whittaker and Feeny, 1970; Levin, 1976; Segal et al., 1980; Berryman, 1982; Coley et al., 1985; Rhoades, 1985). If herbivore numbers are limited by parasites and predators, then the herbivores probably exert little or no selective pressure on the plant host (Hairston et al., 1960; Lawton and McNeill, 1979; Price et al., 1980; Schultz, 1983a, b).

Evolutionary feedback may exert density-dependent control over herbivore/parasite populations. Thus, when herbivore numbers are abundant and the feeding pressure on the plant host is relatively intense, selection in the plant population will favor allelic frequencies and defenses in the plant population that reduce rates of increase of herbivores and, eventually, herbivore numbers. When slugs and snails, for example, feed heavily on bird's foot trefoil, the proportion of its resistant alleles and level of cyanogenesis increase (Jones, 1966, 1979). This increase tends to reduce feeding pressure on the trefoil.

This relationship can be illustrated further. For simplicity, assume that at one locus in the host there are two alleles, A and A′. The rate of increase of the parasite on a susceptible-type host with AA is greater than 1, whereas on a resistant-type host with A′A′ defenses the rate of increase is less than 1. Thus, through selection on a proportion of the two alleles in the host population, herbivore or parasite numbers will increase or decrease until eventually some equilibrium ratio is approached (Pimentel, 1961). When the herbivore population exerts heavy feeding pressure and there is intense selection on the plant host, the frequency of resistant A′ allele will increase in the plant host population. Natural selection acting on the plant host favors the retention of a sufficient proportion of the A′-defense allele (Levin, 1976; Pimentel et al., 1975). Then herbivore numbers and feeding pressure will decline. The host population probably can never develop 100% effective defensive mechanisms against all herbivores because the production and maintenance of these mechanisms must, at some point, become too costly (McKey, 1974; Cates, 1975; Krischik and Denno, 1983; Rhoades, 1985; Rosenthal, 1986). At the point when herbivore numbers have declined to a suitably low level, the host will no longer benefit from spending energy to increase its level of resistance to its predators.

EVOLUTION OF LIVING SYSTEMS

Since the first organisms appeared on Earth several billion years ago, many basic trends in the evolution of living systems have been apparent. First, the living system has become more complex, with an ever-growing number of species. Although the total number of species present on Earth at any one time has grown, more than 99% of all species have become extinct and have been replaced in time with new species better adapted to the developing ecosystem (Allee et al., 1949).

Clearly, the growing number of species has increased the complexity of the existing living system and raised the total volume of living biomass or protoplasm on Earth. The growth in living biomass has made it possible to capture more energy that flows through the living system. At the same time, more resources from the environment are being utilized and are flowing through the living system. Thus, the total size and complexity of the living system has increased its capacity to convert more and more energy and mineral resources into itself. This, increased capacity, in turn, appears to have increased the stability of the living system, making it less susceptible to major fluctuations in the physical and chemical environment.

Additional stability in the ecosystem has evolved via genetic feedback between the parasites and their food hosts. Because the activities of parasites (including herbivores and predators) and hosts are interdependent, stability is essential to their survival. Parasites cannot increase their harvest of food from the host species population indefinitely without eventually destroying their food host and, therefore, themselves. This is not to imply that group selection and self-limitation are dominant activities in natural systems. Hosts under selective pressure may evolve various defense mechanisms to protect themselves from exploitation by parasites (Pimentel, 1988). This evolution takes place primarily by individual selection. Evolution in parasite–host systems, together with complexity in general in the ecosystem, leads to increased stability, and has survival value for natural living systems.

BIOGEOCHEMICAL CYCLES

Several chemical elements, including carbon, hydrogen, oxygen, phosphorus, potassium, and calcium, are essential to the functioning of living organisms and therefore ecological systems. Various biogeochemical cycles have evolved to ensure that plants, animals, and microbes have suitable amounts of these vital elements. Biogeochemical cycles both conserve the vital elements and keep them in circulation in the ecosystem. Indeed, the mortality of living organisms keeps the vital elements in circulation, enabling the system to evolve and adapt to new and changing environments. These biogeochemical cycles are themselves a product of evolution in the living system. If the living system had not evolved a way of keeping vital chemicals in circulation and conserving them, it would have become extinct long ago.

Every organism, whether a single cell, a tree, or a human, requires nitrogen for its vital structure, function, and reproduction. Although the atmosphere is the major nitrogen reservoir, plants cannot use atmospheric nitrogen directly. It must be converted into nitrates, which is often accomplished by nitrogen-fixing bacteria and algae (Figure 4.2). Some of these bacteria have a symbiotic relationship with certain plants such as legumes. These plants develop nodules and other structures on their roots to protect and feed the bacteria. Some plants, for example, provide the associated bacteria with carbohydrates and other nutrients. In turn, the bacteria fix

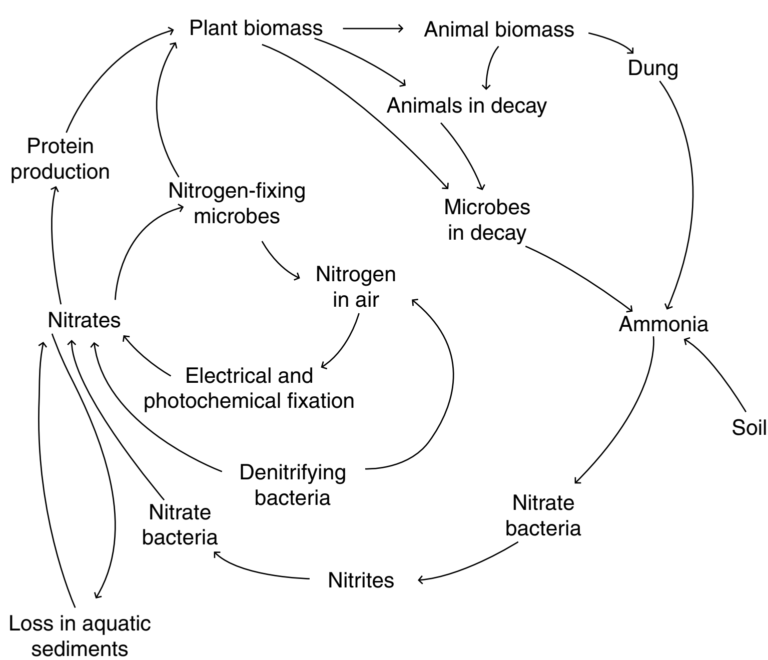

FIGURE 4.2 The nitrogen biogeochemical cycle.

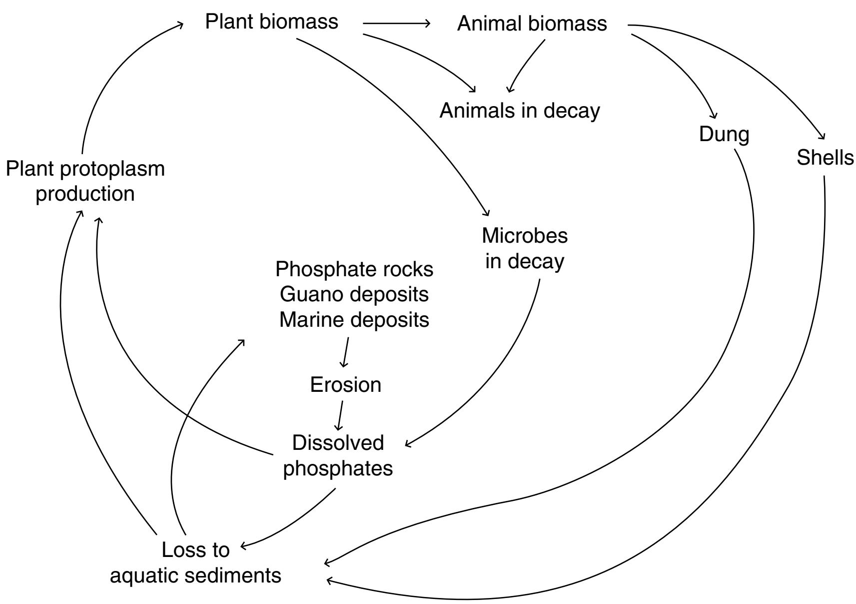

FIGURE 4.3 The phosphorus biogeochemical cycle.

nitrogen for their own and the legume plant's use. In addition, free-living bacteria such as *Azotobacter* and blue-green algae such as *Anabaena* fix atmospheric nitrogen for their own use. When these bacteria and algae die and are decomposed by other bacteria or algae, their nitrogen is released for use by other plants.

The decay of plants, animals, and microbes also recycles nitrogen, but in the form of ammonia (Figure 4.2). Microbes carry out most decomposition of protoplasm. The ammonia released by decomposition of the organic matter is in turn converted by bacteria into nitrates, available for use by plants. Some additional nitrates are produced by electrical storms (Figure 4.2), and some ammonia becomes available to the biological system from volcanic action and igneous rocks.

Phosphorus, another essential chemical element, is recycled by the decomposition of plants, animals, and microbes (Figure 4.3). Additional phosphorus comes from soil and aquatic systems. At the same time, some phosphorus is continually lost to the aquatic system, especially the marine system, when it is deposited in sediments. Like nitrogen and phosphorus, all other essential elements depend on the functioning living system for recycling. Sometimes particular organisms serve special roles in recycling the vital elements. Thus, the living system conserves and recycles the essential elements in the biological system.

AQUATIC ECOSYSTEMS

Water covers approximately 73% of the Earth, but the aquatic life system accounts for only 43% of the total biomass produced annually (Odum, 1978; Pimentel and Hall, 1989). The prime reason for its low productivity is a shortage of nutrients and the second is lack of sunlight penetration into the aquatic system. However, some

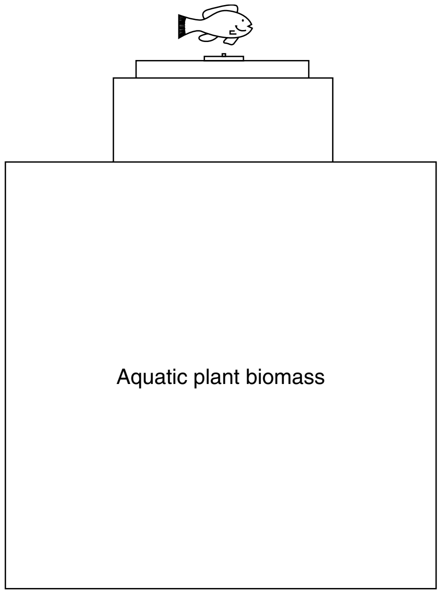

FIGURE 4.4 Trophic pyramid in an aquatic ecosystem indicating the small quantity of fish that might be harvested from the relatively large quantity of aquatic plant biomass.

shallow aquatic systems with ample nutrients are extremely productive, yielding up to 20 tons/ha of plant biomass.

Although aquatic systems may be productive in terms of plant biomass, the production of fish biomass is quite low. Primary producers (phytoplankton) must often pass through three to five trophic levels before the biomass is harvested as fish (Figure 4.4). As only about 10% percent of the energy generally moves from one level to the next, little fish biomass is produced at the top of the food chain. For example, even with 20 tons/ha of plant biomass, the fish harvest is estimated to be only 0.2 kg/ha.

Humans harvest less than 1% of their total food from the aquatic system because of its low productivity. Thus, it is doubtful that the aquatic system is capable of providing more human food in the future. In fact, a future *decrease* is likely because of overfishing and pollution.

TERRESTRIAL ECOSYSTEMS

Land covers only 27% of the Earth, yet this small terrestrial system produces an estimated 57% of the Earth's total biomass (Odum, 1978; Pimentel and Hall, 1989). Forest and agricultural lands account for about 90% of total biomass production. More than 99.9% of human food comes from the terrestrial system and less than 0.1% from the aquatic system (FAO, 2002).

Solar energy powers the ecosystem. During a year the solar energy reaching 1 ha in temperate North America averages about 14 billion kcal (Reifsnyder and Lull, 1965). Nearly half of this, or 7 billion kcal, comes during the 4-month summer growing season. Under favorable conditions of moisture and soil nutrients, the annual production of natural plant biomass in North America averages about 2400 kg/ha (dry) per year.

The productivity of the terrestrial system depends upon the quality of soil, availability of water, energy, favorable climate, and amount and diversity of biological resources present. Agricultural productivity is affected by the same basic factors that influence the productivity of these natural systems.

AGRICULTURAL ECOSYSTEMS

To obtain food, humans manipulate natural ecosystems. In altering the natural system to produce vegetation or animal types (livestock) different from those typical of the natural systems, a certain amount of energy input is necessary. In principle, the greater the change required in the natural system to produce crops and livestock, the greater the energy and labor that must be expended.

This same principle applies in reverse. That is, the more closely the agricultural system resembles the original natural ecosystem, the fewer the inputs of energy and other factors required. Equally important, the closer the agricultural system is to the natural ecosystem, the more sustainable it is, because less environmental degradation takes place in the less intensively managed systems.

The productivity of agricultural plants is limited by the same factors that limit natural plants—sunlight, water, nutrients, temperature, and animal/plant pests. The agriculturalist seeks to maximize the availability of favorable environmental factors for the crop plants while minimizing the impacts of pests.

WATER

Water, followed by nutrients, is the principal limiting factor for terrestrial plant productivity, including agriculture. The United States invests large amounts of fossil energy input in agricultural production into supplying irrigation water (20%) and fertilizer nutrients (30%) (Pimentel and Wen Dazhong, 1990). Agricultural practices that help to conserve water and soil nutrients not only contribute to crop productivity but also reduce the costly fossil energy inputs in the system (Pimentel et al., 1987). Water and soil nutrients can best be conserved by controlling soil erosion and water runoff. These steps also maximize the amount of soil organic matter present, which helps maintain nutrients, water, tilth, and the buffering capacity of the soil. All of these characteristics, combined with ample water and soil nutrients, help keep the agroecosystem productive.

As in natural ecosystems, the goal in agriculture should be to conserve nutrients and water for optimal production while maintaining the stability of the system. In agriculture, this would mean recycling manure, crop residues, and other wastes.

NUTRIENTS

After water, soil nutrients (nitrogen, phosphorus, potassium, and calcium) are the most important factors limiting crop productivity. Valuable nutrient resources available for recycling include crop residues and livestock manure. Crop residues total about 430 million tons/year. This amount of crop residue contains about 4.3 million tons of nitrogen, 0.4 million tons of phosphorus, 4.0 million tons of potassium, and 2.6 million tons of calcium. The total amount of livestock manure produced annually in the United States is about 1.2 billion tons. This manure contains about 2.5 million tons of nitrogen, 600,000 tons of phosphorus, and 200,000 tons of potassium (Troeh and Thompson, 1993). These quantities of nutrients in both the residues and manure are significantly greater than the quantities of commercial fertilizer applied annually in the United States, which contain 12 million tons of nitrogen, 5 million tons of phosphorus, and 6 million tons of potassium. Except for the extremely small amount of crop residues that are harvested annually, most of the crop residues are recycled on U.S. agricultural land. However, estimates are that only 0.5 million tons of the total nitrogen in the manure are recoverable and usable with present technology. Some of the difficulty is due to the uneven distribution of livestock and crop areas. About 30–90% of the nitrogen is often lost through ammonia volatilization when manure is left on the surface of croplands and pasturelands (Vanderholm, 1975). However, less than 5% of the nitrogen is lost as ammonia when the manure is plowed under immediately.

The major cause of soil-nutrient loss in the United States is soil erosion (Pimentel, 1993; Pimentel et al., 1995). Average soil erosion rates are 10 tons/ha/year (NAS, 2003). A ton of rich agricultural soil contains about 4 kg of nitrogen, 1 kg of phosphorus, 20 kg of potassium, and 10 kg of calcium. For nitrogen alone, 20 tons of soil contains 80 kg/ha, which is almost half of the average of 155 kg/ha of nitrogen fertilizer that is applied to U.S. corn.

Soil erosion selectively removes different components from the soil. Eroded material usually contains 1.3 to 5 times more organic matter than the remaining soil (Allison, 1973). Soil organic matter is extremely important to the productivity of the land because it helps retain water in the soil and improves soil structure and cation exchange capacity. In addition, organic matter is the major source of nutrients needed by plants (Volk and Loeppert, 1982). About 95% of the nitrogen in the surface soil is stored in the organic matter.

U.S. farmers apply 12 million tons of nitrogen as commercial fertilizer annually, with a total value of $15 billion. Microbes fix about 14 million tons of nitrogen in the United States annually (Delwiche, 1970). This nitrogen has an economic value of nearly $12 billion today.

The harvest of the corn crop itself removes from 25% to 50% of the total nitrogen applied. Some nitrogen (15–25%) is lost by volatilization and 10–50% by leaching (Schroder, 1985).

Pest Controls

In seeking to achieve pest control, agriculturalists would do well to mimic the natural system. They can do so by maintaining the genetic resistance of crops to pests such as insects, plant pathogens, and weeds; encouraging pests' natural enemies; employing crop rotation and other crop diversity patterns; and utilizing natural forage and trees where appropriate (Pimentel, 1991). For example, the spotted alfalfa aphid is kept under biological control through the introduction of natural enemies and using alfalfa varieties naturally resistant to the aphid (PSAC, 1965).

Crop rotation can be highly effective in pest control, as demonstrated with the control of the corn rootworm complex (Pimentel et al., 1993). In addition to aiding in insect control, crop rotation may also help reduce disease and weed problems.

In the United States, most plant pathogens are controlled through plant host resistance. It is estimated that nearly 100% of all crops planted in the nation contain some degree of enhanced resistance to pests (Pimentel, 1991). Farmers can also prevent disease by planting disease-free propagated material and by using other cultural methods that eliminate the source of the inoculum.

Weed control is accomplished through mechanical tillage, rotation, various polycultural means, and herbicides (Pimentel, 1991). Options for weed control are generally fewer than options for insect and plant pathogen control.

Agricultural Ecosystem Stability

A relatively stable natural ecosystem increases the stability of the human food supply. Over time, humans have enhanced agricultural stability by selecting crops and livestock that are best adapted to particular environments. In addition, they have used increased energy inputs to enhance or control various aspects of the agricultural environment. For example, natural nutrient limitations have been offset by the addition of fertilizers, water shortages overcome by irrigation, and pest attacks controlled by pesticides and various cultural and biological controls.

Species Diversity

Wild plants and animals are the original sources of genetic material used for breeding resistance to pests and improving other crop and livestock features that contribute to increased yields.

Unfortunately, because of the conversion of extensive natural ecosystems into agricultural land, thousands of species are being lost each year (Ehrlich and Ehrlich, 1990; Wilson, 1988). The most rapid loss of biological diversity is occurring in tropical forests and savannas, the same regions where most crop and livestock species originated. This loss has alarming implications for future production of human food, important medicines, and other products that are obtained from biological resources.

Crop Yields

On rich agricultural soils with ample water and fertilizers, the average biomass production for several major crops is about 15 tons/ha. However, under relatively poor agricultural conditions, biomass yields may range from only 0.5 to 1 tons/ha. Forests on good soils, with ample water and nutrients, and at the proper growth stage may reach a yield of 15 tons/ha. However, on average the yield of forests is about 3 tons/ha.

Under favorable atmospheric conditions and with the addition of nitrogen, phosphorus, potassium, and calcium fertilizers, hybrid corn, one of our most productive crops, will yield annually about 18,000 kg/ha of biomass (dry) or 9000 kg/ha of grain. Wheat production in North America averages about 7000 kg of biomass/ha, or about 3000 kg/ha of grain. Both these yields are much higher than the yield of natural vegetation. However, many agricultural crops are less productive than either corn or wheat, and overall average crop biomass production is probably close to that of natural vegetation.

To convert corn biomass to heat energy, the 18,000 kg/ha yield is multiplied by 4000 kcal/kg, yielding 72 million kcal/ha. This represents only 0.5% of the total solar energy reaching 1 ha during the year. The percentage of solar energy harvested as wheat biomass is 0.2%. Natural vegetation, producing about 2400 kg/ha, converts about 0.1% of solar energy into biomass. This 0.1% is the average conversion for all natural vegetation in North America and is about the average for U.S. agriculture.

From the total of 18,000 kg/ha of corn biomass, as mentioned above, humans are able to harvest approximately half, or 9000 kg/ha as food. This is obviously much more than what hunter-gatherers were able to harvest per hectare from the natural environment. Natural ecosystems yield only about 2400 kg/ha of plant biomass, only a small portion of which would be converted into animal and microbe biomass.

Annual versus Perennial Crops

Most crops cultivated in the world are tropical annuals. The fact that most human societies probably originated in the tropics may explain in part why so many crop and livestock species originated there. Originally, annuals were a practical choice for crops, because pest problems, particularly weeds, could be minimized and the land could be cleared of all vegetation by burning and digging. This gave newly planted crops a head start on weeds and other potential pests (Pimentel, 1977).

At present, 90% of the world's food supply comes from only 15 species of crop plants and 8 species of livestock (Pimentel et al., 1986). This is a very narrow base, especially considering that there are about 10 million species of plants and animals in the world today.

The human food supply would be enhanced if it could rely on more perennial crops, especially grains (Pimentel et al., 1986). Because grain crops supply approximately 80% of the total food produced worldwide, the development of perennial grain crops would add stability to the food supply and the agricultural ecosystem. A perennial crop is one that might have to be replanted only once every 5 years.

The advantages of perennial grain crops in particular are manifold. First, the soil would not have to be tilled each year. Annual soil tillage requires enormous amounts of fossil, draft animal, and human energy. The energy required to till 1 ha ranges from 200,000 kcal for hand tillage to nearly 600,000 kcal for a small tractor. Further, decreasing tilling would conserve soil and water resources, yielding additional energy savings. Erosion and runoff occur primarily when the soil is tilled and exposed to rain and wind. Vegetative cover is the principal way to protect soil and water resources (Pimentel et al., 1995), so a perennial grain crop would be valuable in decreasing erosion in world agriculture.

At present there are no commercial perennial grain crops, and their development will depend in part on genetic engineering, which in turn depends on maintaining biological diversity. Nature provides the genes that humans use to develop new crop and livestock types. New genetic materials will also be important for use in food processing and the development of new drugs and medicines. Unfortunately, scientists have not had time to investigate the full potential of the world's natural biological resources.

Clearly, much can be learned from natural systems about maintaining the productivity and sustainability of agricultural systems. If the agricultural production system could be designed to more closely resemble natural ecological systems, it would require fewer energy inputs and be more productive and sustainable.

FOOD NEEDS FOR FUTURE GENERATIONS

The degradation of agricultural land, forests, and other biological resources greatly affects their productivity. Today the productivity of these resources is being maintained in large measure by the increased input of fossil energy for fertilizers, pesticides, and irrigation. Thus, it will be a challenge to meet the food needs of the rapidly expanding human population. Food production in all countries—especially in the developing nations, where the population growth rates are high and the generation times short—must increase at a greater rate than ever before.

A study by the National Academy of Sciences (1977) targeted eight food sources for increase: rice, wheat, corn, sugar, cattle, sorghum, millet, and cassava. These foods provide 70–90% of all the calories and 66–90% of the protein consumed in developing countries. Instead of increasing, cereal grains per capita have been decreasing since 1984. Thus, for the past 20 years, grains per capita have been in continuous decline (FAO, 1961–2004).

Growing food grain exports in the early 1970s encouraged the United States and other developed countries to expand their production (Webb and Jacobsen, 1982). Owing to these encouraging trends, many U.S. farmers purchased more land and invested heavily in new machinery. However, a few years later the situation turned around: OPEC increased oil prices, making it necessary for developing countries to spend their limited funds for imported oil instead of imported food. This change depressed the agricultural markets in most of the developed nations, a situation that continues to date.

The rapidly growing world population will have a staggering impact on food and natural resources (Pimentel and Pimentel, 2003). Even if individual dietary patterns are modified to include less animal products and more plant foods such as grain, food production must be greatly increased. The message is clear: more food—much more—will have to be grown to sustain the rapidly growing human population of the future.

REQUIREMENTS FOR SOLVING FOOD PROBLEMS

To increase food supplies for current and future populations, humans must protect the environment, develop new technologies, and limit human population growth.

Safeguarding the Environment

The environmental resources for food production, including land, water, energy, forests, and other biological resources, must be protected if food production is to continue to grow. Over the past four decades, humans have allowed environmental resources to degrade. As noted, we have been offsetting this degradation with fertilizers, irrigation, and other massive inputs—all based on fossil energy. Thus, we have been substituting a nonrenewable resource for a renewable resource. Clearly, this has been a dangerous, if not a disastrous, policy.

Science and Technology

Recent decades have witnessed many exciting and productive technological advances that have increased food supplies. For example, advances in plant genetics for some major crops have raised the "harvest index." In addition, agricultural chemicals, pesticides, and fertilizers have helped increase yields of food and fiber crops per ha. Improved processing methods have enabled the food supply to be safely extended beyond harvest time, and the growing transportation network has moved more food from production sites to far-distant markets. In the industrialized nations, the result has been a more abundant, more nutritious, and safer food supply. People living in developing nations, however, have not been as fortunate, although enhanced breeds such as high-yielding rice have benefited millions in the Far East.

The new genetic engineering technology offers further promise of raising crop and livestock production and improving the use of some major resources. This will be especially true if, for example, we can develop rice, wheat, corn, and other cereal grain crops that will fix nitrogen, as legumes do. Of the essential nutrients, nitrogen fertilizer requires the largest fossil energy input. Thus, developing cereal grains that fix nitrogen will be a major breakthrough. However, conservative estimates of when this breakthrough will be achieved range from 20 to 30 years in the future.

Some of the other promised benefits of genetic engineering, such as plants that grow with little or no water, are without scientific basis. Even if many of the promises of biotechnology are forthcoming, it is essential that quality soil, water, and biological resources are maintained.

Biotechnology and other new technologies undoubtedly will help conserve energy resources and facilitate increased food production. Sufficient, reliable energy resources will have to be developed to replace most of the fossil fuels now being rapidly depleted. These new sources likely will be more costly than fossil fuels in terms of dollars and the environment. Solar, fission, perhaps fusion, and wind energy will become more viable in the future than they are today. But if we rely solely on new technological advances, we face major problems if the "lottery" of science does not pay off. These developments may not materialize as rapidly as needed to meet future needs. One has only to observe the plight of millions of people in Calcutta and Mexico City to recognize that science and technology have done little to improve their lives during recent decades. Per capita food supply (grains) has been declining for the past 20 years. Clearly, technology has not been able to keep food supplies increasing as rapidly as world population.

Population

Thus far, only factors affecting food production have been considered. But production is only one side of the food equation. The other is the demand, or rate of consumption. This is determined by the size of the human population. Ultimately, the size of the world population will determine the need for food. When human numbers exceed the capacity of the world to sustain them, then a rapid deterioration of human existence will follow. As it does with all forms of life, nature ultimately will control human numbers.

Strategies for increasing food production substantially over present levels and decreasing population growth must be developed now. Both parts of the food equation must be brought into balance if future generations are to have an adequate food supply and live in a world that supports a reasonably acceptable standard of living.

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