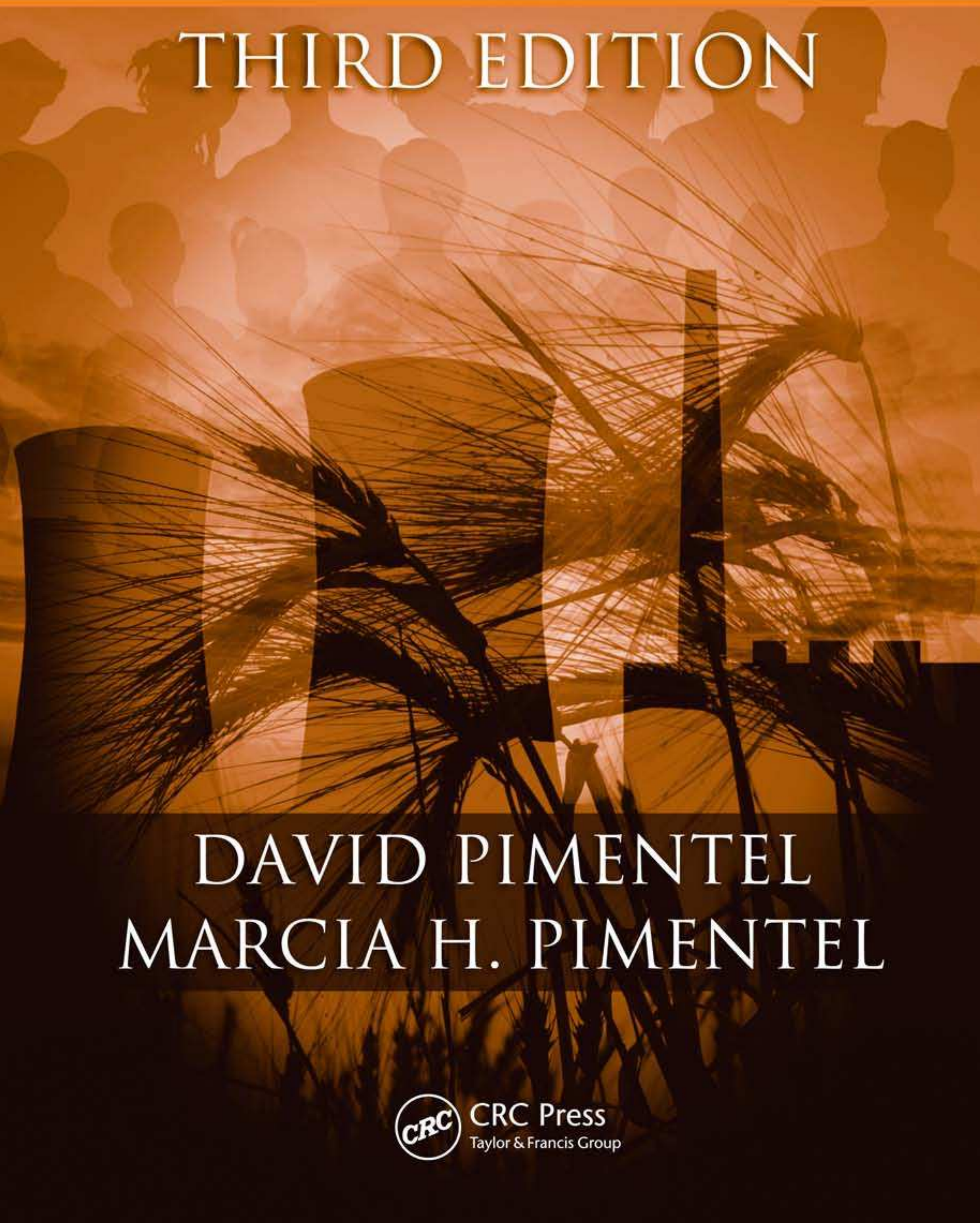
FOOD, ENERGY, AND SOCIETY

THIRD EDITION



DAVID PIMENTEL
MARCIA H. PIMENTEL

CRC Press
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Preface

In the more than 25 years since the publication of the first edition of *Food, Energy, and Society*, the world's natural resources have become more stressed in the face of rapid expansion of the world population. In less than 50 years the world population has doubled, world food supplies have dwindled, and supporting energy, water, land, and biological resources have come under great pressure. Now in the twenty-first century, the ecological integrity of world resources is threatened with many species facing extinction. In the face of these major changes, this third edition presents an updated and expanded perspective and analysis of the interdependency of food, energy, water, land, and biological resources.

Large numbers of humans throughout the world are facing hunger and malnutrition because of political struggles and the overwhelming increase in population. The World Health Organization reports there are 3.7 billion who are malnourished. This is the largest number ever in history, and signals a serious food problem now and certainly for the future. Since 1984, food production, especially cereal grain production, has been declining per capita because of growing numbers of people, shortages of energy in agricultural crop production (e.g., fertilizers), and shortages of freshwater.

Humans use energy from many sources to grow food, provide shelter, maintain health, and improve their well-being. The energy source, whether from the sun, human energy, animal power, or fossil fuels, and its abundance influence all human activities and personal security. As society has evolved, so have energy needs and uses. Early humans who hunted and gathered their food in the wild depended primarily on their own energies. Even now many people in developing countries augment personal energy with animal and human power, firewood, and other resources.

In contrast, ample affordable fossil energy supplies have supported intensive agriculture, industry, and transport in developed nations. However, along with increased population numbers, the per capita availability of fossil energy has been declining worldwide. This is because reserves of these finite energy resources are decreasing. The United States now imports 63% of its oil at a cost of $120 billion per year. The imports are projected to increase to 95% by 2020 and the possibility is $10 per gallon gasoline at that time. Petroleum geologists project about 40 years of oil and natural gas resources for the world. The United States has 50–100 years of coal reserves. Societies that now rely 97% or more on fossil fuels need to develop sustainable, renewable energy sources. Of course, renewable energy depends on water, land, and biological resources and at substantial environmental and economic costs.

Along with energy, fertile land is a critical resource for food production. The Food and Agricultural Organization (FAO) reports that 99.9% of all food (calories) comes from the land. At a time when more cropland is needed, valued fertile soil is being lost because of erosion that is 10–30 times faster than sustainability. With this environmental impact, crop yields decline, or more fertilizers and pesticides (fossil energy dependent) are used. Obviously on a per capita basis, cropland resources are declining and now are less than one-half of what is needed for a diverse diet for the world population.

Freshwater is vital to all plants, animals, and humans. For cereal grains, for example, about 1000 L (265 gal) of freshwater are required on average to produce 1 kg (2.2 pounds) of these grains. Approximately 17% of all crops are irrigated and this irrigation provides the world with 40% of its food. World agriculture consumes from 70% to 80% of the freshwater and currently serious shortages exist in many regions. This is one of the major limits to world food production.

David Pimentel and Marcia H. Pimentel

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1 Energy and Society

Adequate food, water, and shelter are basic to human survival. Closely linked to these life essentials is an adequate energy supply, for humans have always used energy to obtain food, water, shelter, and protection from parasites and predators. Over the centuries people have employed energy from many sources. First they depended on their own energy and natural energy from sunlight; later they relied on fire, draft-animal power, and water and wind power. Still later they invented engines fueled by wood, coal, petroleum, and, more recently, nuclear energy. Humans have used these various energy resources to modify and manipulate land, water, plants, and animals to fulfill their survival needs. Finding, controlling, and using energy has enabled humans to progress from an unsettled, primitive lifestyle to a more settled and sophisticated lifestyle. Among the mammals, only the humans can think creatively and develop advanced technologies.

The attainment of security and stability depends on the use of energy. For example, humans expend energy to control disease; to obtain, purify, and store water; to produce pesticides; to produce antibiotics and other drugs; and to implement public health measures. All of these have enhanced the quality of human life.

Security and stability also entail the protection of one person from another and one group of people and their resources from encroachment by rivals. Social harmony depends not only on the rules established by governments but also on the effectiveness of societal forces used to enforce the laws. Governments, police, and military forces all expend enormous amounts of energy. In the so-called civilized society of nations of the world today, governments, police, and military forces use more energy than farmers to produce food on the farm for the population being governed.

The availability of increasing energy supplies enabled humans to develop a societal structure more complex than that of the early hunter-gatherers. The present pattern of energy use contrasts sharply with that of the distant past, when finding adequate food dominated people's daily activities. White (1943) proposed that humans evolved in the following three major stages: (1) savagery—hunter-gatherers living on wild foods; (2) barbarianism—early agriculture and pastoral societies; and (3) civilization—development of engines and intensive use of fossil energy to produce food and necessities.

Each step signified major changes in both the type of energy supplies and their use by humans. In fact, White felt people would have remained on the "level of savagery indefinitely if [they] had not learned to augment the amount of energy under [their] control." The total quantity of energy controlled by humans grew to include a surplus above the amount needed for their basic needs.

DEVELOPMENT OF SOCIETIES AND ENERGY

Hunter-gathering societies were small, rarely having more than 500 individuals (Service, 1962; Lee and DeVore, 1976), and simple (Bews, 1973). As securing food and shelter consumed so much time and energy, other activities scarcely existed. With the development of agriculture, more dependable supplies of food, fiber resources, and surplus energy became available. Concurrently, a greater incentive for increased productivity and a greater interdependence among people evolved in human societies. As the stability of the food supply increased, societies that had once been seminomadic, following their food supply, gained in security and permanence.

In early agricultural societies food production still dominated human activities, and as a result the range of social interactions remained relatively narrow. Then the introduction of draft-animal power into agricultural production decreased human power expenditure and increased free personal time (see Chapters 7 and 10). People gained the freedom to participate in various activities and social systems became more complex. Over time, water and wind emerged as excellent energy resources. Instead of using draft animals that required energy for feed and care, people used waterwheels and windmills. With this change, humans had more power at their disposal and at a lower cost (calculated as human energy input) than in the past. In this way, the amount of surplus energy available to society was greatly increased.

The use of water and wind power and the subsequent reduction of dependence on animal power fostered the development of trade and transport between societal groups. Improved communications expanded the exchange of resources and ideas between groups. Technical advances spread more easily than ever before. Further developments in science and technology resulted in the invention of sailing ships, which enhanced communication, transportation, and trade. With these changes human activities diversified, and specialized disciplines such as farming, sailing, trading, and industry developed.

The invention of the steam engine was a highly significant milestone in energy use, for it signaled the beginning of the use of fossil fuels as an energy source. Later engines used coal and oil as fuels, providing humans with immense power to control their environment and to change the total economic, political, and social structure of society (Cook, 1976). Along with these changes came greater stability, even greater specialization of work, longer life spans, and improved diets.

ENERGY FROM FIRE

Since the earliest human societies, energy from fire has played a dominant role in survival. Although primitive people feared fire, they learned to control and constructively use its energy about half a million years ago. Fire enabled hunter-gatherers to ward off large animal predators and helped them clear vegetation, which provided further protection. Campfires also provided warmth in cold weather.

In addition, fires made it possible to cook foods, often making them better tasting, easier to eat, and easier to digest. Perhaps more important, cooking reduced the danger of illness from parasites and disease microbes that often contaminate raw foods. Heating also destroys some microbes responsible for food spoilage, so fire could be used to dry and preserve surplus foods for later consumption. This advance helped stabilize the availability of food supplies long after the time of harvest.

When primitive agriculture was developing, about 10,000 years ago, people set fires to clear trees and shrubs from the cropland and grazing areas. This simple procedure also helped eliminate weeds that competed with the crops. Furthermore, the ashes added nutrients to the soil and enhanced crop productivity. After cultivating crops on a certain plot for a few years, early farmers abandoned the land and cultivated other plots fertile enough to support crop growth. This form of early agriculture is termed “slash and burn” agriculture.

Wood from trees and shrubs served as the principal source of fuel for fires, although some grasses and other vegetation were also burned. When there was a relatively small human population, ample supplies of renewable energy in the form of wood were available. Today, with 6.5 billion people on Earth, firewood and other forms of biomass are in short supply in most parts of the world.

ENERGY AND THE STRUCTURE OF SOCIETIES

Early hunter-gatherer societies had minimal structure. A chief or group of elders usually led the camp or village. Most of these leaders had to hunt and gather along with the other members because the surpluses of food and other vital resources were seldom sufficient to support a full-time chief or village council.

The development of agriculture changed work patterns. Early farmers could reap 3–10 kg of grain from each 1 kg of seed planted. Part of this food/energy surplus was returned to the community and provided support for nonfarmers such as chieftains, village councils, men who practice medicine, priests, and warriors. In return, the nonfarmers provided leadership and security for the farming population, enabling it to continue to increase food/energy yields and provide ever larger surpluses.

With improved technology and favorable conditions, agriculture produced consistent surpluses of the basic necessities, and population groups grew in size. These groups concentrated in towns and cities, and human tasks specialized further. Specialists such as masons, carpenters, blacksmiths, merchants, traders, and sailors developed their skills and became more efficient in their use of time and energy. The goods and services they provided brought about an improved quality of life, a higher standard of living, and, for most societies, increased stability.

Ancient Egypt is an outstanding example of an early society that not only possessed environmental resources favorable to agriculture but also developed effective agricultural technology (Cottrell, 1955). The Nile’s yearly floods deposited nutrient-rich silt on the adjacent farmland and kept it productive. The river was also a reliable source of water for irrigation. Additionally, the warm Egyptian climate was highly favorable for crop production. This productive agricultural system supported the

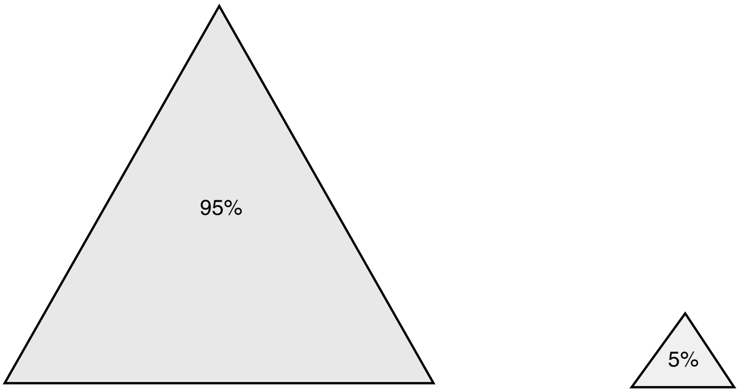

FIGURE 1.1 During the age of the Pharaohs and pyramid projects, ancient Egypt had a population of 3 million. About 95% of society was involved in agriculture. The surplus energy of about 5% was utilized for the Pharaohs and the construction of the great pyramids.

95% of the Egyptian population that was directly involved in agriculture (Figure 1.1) and provided enough surplus food to sustain the 5% of the population that did no agricultural work (Cottrell, 1955).

Relatively little food energy was needed to support the small ruling class. Furthermore, Egypt's naturally isolated location provided protection from invasion, so the society did not have to expend large amounts of energy to maintain a military class. As a result, the Pharaohs could and did use the 5% of the population not involved in agriculture as slave laborers to build pyramids and stock them with goods and materials for a life that, Egyptians believed, would come after life on Earth.

During this early period the Egyptian population remained relatively constant because of rulers' demands for slaves. As soon as surplus men were mature enough for work, they were assigned to pyramid construction and literally worked to death during the few years of slave labor. When they died, they were replaced with new surplus labor. This system was sustained without jeopardizing the fundamental agricultural system that involved the efforts of almost all the Egyptian people.

During the age of the Pharaohs, which spanned the years from 2780 to 1625 B.C. (Fakhry, 1969), Egypt had a population of about 3 million, much less than the 74 million of today. A 5% food/energy surplus from about 3 million people is not much; on a per capita basis, this ranges from 100 to 150 kcal per day (Cottrell, 1955), or the equivalent of 10–15 kg of surplus wheat per person per year. Based on 3 million people, this totals 30–45 million kg of surplus wheat per year.

The construction of the Cheops pyramid over a 20-year span used an amount of energy equal to the surplus energy produced in the lifetime of about 3 million Egyptian people (Cottrell, 1955). During the construction period the pyramid work force was about 100,000 slaves per year. Assuming that each slave received 300–400 kg of grain per year, the total cost would be 30–40 million kg of grain, or the entire food/energy surplus produced by the Egyptian agricultural community.

Later in its history, Egypt used surplus resources to support large military forces and conquer some of its neighbors. These military operations not only secured additional land and food but also brought many conquered people back to Egypt to be slaves. But the vast deserts over which the Egyptian forces had to travel and transport supplies naturally limited the military operations. Ever-increasing quantities of energy had to be expended simply to protect the supply routes and transport military provisions.

At other times, when the population became large relative to the land and the agricultural resources, agricultural surpluses were not available in Egypt. In these relatively overpopulated conditions and with shortages instead of surpluses, the Egyptian society was just able to maintain itself. Sometimes civil strife and social problems developed. These conditions often led to a decline in population because these unstable societies were unproductive in agriculture or any other essential activity.

Thus, Egypt's early history provides a prime example of the role that energy, as measured by food surpluses, played in the structure and activities of a society. Although the structures of today's societies are far more complex than that of ancient Egypt, energy availability and use continue to be major factors in the standard of living.

FOOD AS A FOCAL POINT OF SOCIETIES

In natural communities, the entire structure and function of the population revolves around food as an energy source (Elton, 1927). This situation is also true of human societies. Primitive societies used food as the medium of exchange long before money was used. They traded surpluses of crops and in this way not only improved their own diets but also had the opportunity to interact with other groups.

The populations of all species are influenced by the relation between food supplies and demand. As with human societies, stability has advantages for a biotic community's survival and therefore is an important evolutionary trend (Pimentel, 1961, 1988). Evolved balance in supply–demand economies of natural populations contributes to the relative stability that is observed in these dynamic community systems.

The major reason why food and energy are considered critical resources for all natural communities, including humans, is that living plants can convert relatively limited amounts of solar energy—only about 0.1% of the sunlight reaching the Earth—into biomass. Before fossil fuels were discovered and used, humans shared with other animals that portion of the sun's energy captured by plants and subsequently converted to food/energy.

In prehistoric times, humans acknowledged the importance of food in their lives, as revealed in the many pictures of animals and food plants they painted in caves and on tools (Figure 1.2). Egyptian artwork pictures various food crops and livestock, and grains and other food items were customarily buried with the dead. The Mayan civilization of Central America depended on corn (maize) as its staple food and produced numerous sculptures and paintings of corn.

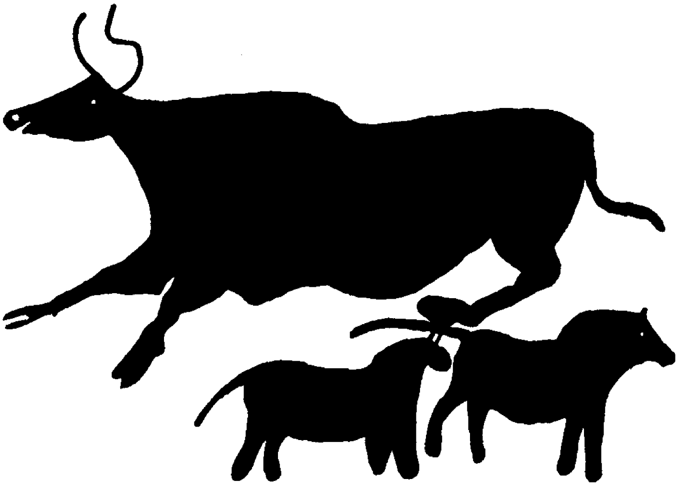

FIGURE 1.2 Drawing of a cow and several small horses in the painted cave of Lascaux, France.

Many religious and cultural groups celebrated successful harvests with ceremony and pageantry.

USE OF ENERGY IN FOOD SYSTEMS

One measure of the relative importance of food in society as a whole is the amount of energy and labor devoted to producing it. In prehistoric times, about 95% of the total energy expended by the family was used for food. This included hunting and gathering, transporting the food back to camp, and preparing it for consumption.

Even today in some developing countries, the energy expended on food systems represents 60–80% of the total expended energy (RSAS, 1975). By contrast, in many developed countries the proportion of energy devoted to food production ranges from 15% to 30%, and little of this is human energy. For example, in the United States, the amount of energy expended on food production represents about 19% of the total energy used. In the developing countries, this percentage includes energy used for production, processing, packaging, distribution, and preparation of food.

Although the United States spends but 19% of its total energy on food, the overall quantity of energy it uses is several times that used in the less complex societies of developing countries (Figure 1.3). The United States expends three times as much energy per capita for food production as the developing countries for all energy-consuming activities including food production. This comparison emphasizes once again the energy-intensive lifestyle that has developed in such countries as the United States following the ready availability and low cost of fossil-fuel energy resources.

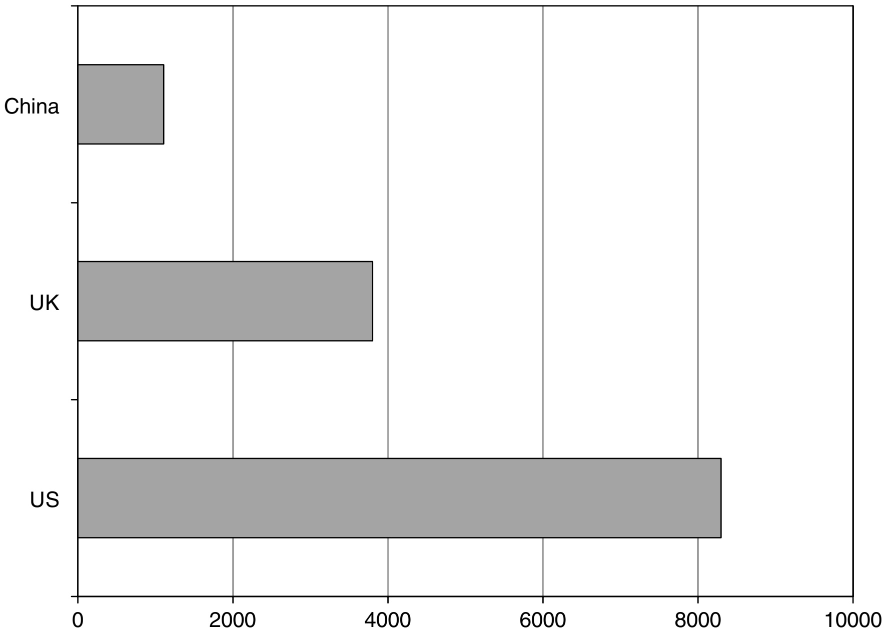

FIGURE 1.3 Energy consumption rates per capita per year in gallons of oil equivalents in the United States, the United Kingdom, and China (1 gal = 3.78 L).

REFERENCES

Bews, J. 1973. *Human Ecology*. New York: Russell & Russell.

Cook, E. 1976. *Man, Energy, Society*. San Francisco, CA: W.H. Freeman.

Cottrell, F. 1955. *Energy and Society*. Westport, CT: Greenwood Press.

Elton, C.S. 1927. *Animal Ecology*. London: Sidgwick and Jackson, Ltd.

Fakhry, A. 1969. *The Pyramids*. Chicago, IL: University of Chicago Press.

Lee, R.B. and I. DeVore. 1976. *Kalahari Hunter-Gathers*. Cambridge, MA: Harvard University Press.

Pimentel, D. 1961. Animal population regulation by the genetic feedback mechanism. *American Nature* 95: 65–79.

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

Royal Swedish Academy of Sciences (RSAS). 1975. *Energy Uses*. Presented at Energy Conference, Aspenasgarden, October 27–31. Stockholm, Sweden: Royal Swedish Academy of Sciences.

Service, R. 1962. *Primitive Social Organization*. New York: Random House.

White, L.A. 1943. Energy and the evolution of culture. *American Anthropologist* 45: 335–354.

2 Energy and Power

ENERGY AND WORK

Energy is defined as the capacity to do work. Although energy is found in many forms (Table 2.1), all forms have the capacity to do work. Light energy coming from the sun is the most important and universal type of energy, supporting all life on Earth. Plants have the capacity to capture, or “fix,” light energy and convert it into chemical energy, which is used by the plants themselves and the animals that feed on them. Many human activities, most prominently agriculture and forestry, rely on solar energy. Solar energy is also fundamental to wind power, hydroelectric power, and other types of energy systems.

Radio, radar, micro, and television waves use electrical energy. The lifting or moving of objects by humans or machine is a form of mechanical energy. Another form of energy—heat generated by the burning of wood, coal, oil, or gas—is used for cooking and to drive engines. Magnetic energy, which is produced from the interaction of positively and negatively charged matter, can be used to do work. Sound waves, another form of energy, are used in communications and other activities. A more recently discovered form of energy is nuclear energy, which is released from the bound atomic particles in, for instance, uranium. Humans have employed nuclear energy not only to create devastating bombs but also to produce electricity.

LAWS OF THERMODYNAMICS

The use or flow of energy is governed by the two laws of thermodynamics. The first law of thermodynamics states that energy may be transformed from one type into another (Table 2.1) but can never be created or destroyed. For example, light energy can be transformed into heat energy or into plant-food energy (chemical energy). In the process of this transformation, no energy is lost or destroyed; only its form is changed.

The second law of thermodynamics states that no transformation of energy will occur unless energy is degraded from a concentrated form to a more dispersed form. In the real world, all energy transformations take place in open systems because processes necessarily interact with their environment over finite time periods. Thus, according to the second law, in the real world no transformation is 100% efficient.

The second law states the existence of a spontaneous “direction” for energy transformations. For example, if a hot object is placed next to a cool object, heat will flow from the hot object to the cool one but never in the reverse direction.

TABLE 2.1

Some Examples of Energy Conversion and Energy Converting Devices

To	From Mechanical	From Thermal	From Acoustical	From Chemical	From Electrical	From Light
Mechanical	Oar Sail Jack Bicycle	Steam engine	Barograph Ear	Muscle contraction Bomb Jet engine	Electric motor Piezo-electric crystal	Photoelectric door opener
Thermal	Friction Brake Heat pump	Radiator	Sound absorber	Food Fuel	Resistor Spark plug	Solar cooker Greenhouse effect
Acoustical	Bell Violin Wind-up phonograph	Flame tube	Megaphone	Explosion	Telephone receiver Loudspeaker Thunder	
Chemical	Impact detonation of nitroglycerine	Endothermic chemical reactions		Growth and metabolism	Electrolysis	Photosynthesis Photochemical reactions
Electrical	Dynamo Piezo-electric crystal	Thermopile	Induction microphone	Battery Fuel cell	Transformer Magnetism	Solar cell
Light	Friction (sparks)	Thermoluminescence		Bioluminescence	Light bulb	Fluorescence

Source: After Steinhart, C. and Steinhart. J., *Energy Sources, Use and Role in Human Affairs*, Duxbury Press, North Scituate, MA, 1974.

Because no transformation is 100% efficient, the temperature of the cool object will rise, but not enough to account for all the energy that is transferred from the hot object. In the transfer, some energy is dispersed into the environment. Consider the example of a cup of boiling water mixed with a cup of cold water. The temperature of the resulting mixture is slightly lower than would be calculated by measuring the energy lost by the boiling water. The cold water is much warmer than it was initially, but because some of the heat energy is lost to the environment, it will not be as hot as the average of the two initial temperatures.

All biological systems, including crops, follow the second law of thermodynamics when solar energy (a high-energy form) is converted into chemical energy. Plants utilize this chemical energy in the process of building their own tissue. Some of the energy being changed from light to chemical energy is lost as heat that dissipates into the surrounding environment.

MEASURES OF ENERGY AND POWER

The basic unit of energy, following the International System (SI) of units, is the joule (J), but many other units of energy are used, such as the calorie, Btu (British thermal unit), quad, kWh (kilowatt hour), TOE (metric tons of oil equivalent), and TCE (metric tons of coal equivalent). Both the calorie and Btu, which are probably the most frequently used units, are based on measurements of heat energy. A calorie, or gram-calorie, is the amount of heat that is needed to raise 1 g of water 1°C at 15°C. The Btu is the amount of heat needed to raise 1 pound of water 1°F. Note that heat measurements are related not to the direct ability to do work but to the capacity to raise the temperature of matter or to change the state of matter (solid, liquid, or gas).

Conversion factors for energy units are listed in Table 2.2. Note that the kilocalorie (kcal), or kilogram-calorie, equals 1000 calories, or gram-calories. The large Calorie, used in the field of nutrition, equals 1 kilocalorie or 1000 (small) calories.

Measurements of energy do not take into account the time required for the conversion process. Work, however, requires the expenditure or use of energy

TABLE 2.2
Energy Conversion Factors

Unit	Equivalents
1 kilojoule (kJ)	1000 joules (J)
1 kilocalorie (kcal)	1000 calories (cal); 4.184 kJ; 4184 J
1 British thermal unit (Btu)	0.252 kcal; 1.054 kJ; 1054 J
1 quad	1015 Btu; 0.252 × 1015 kcal; 1.054 × 1018 J
1 kilowatt hour (kWh)	3413 Btu; 860 kcal; 3.6 MJ
1 horsepower hour (HPh)	0.746 kWh; 2546 Btu; 642 kcal; 2.69 MJ
1 ton of coal equivalent (TCE)	7 × 106 kcal; 29.31 GJ
1 ton of oil equivalent (TOE)	107 kcal; 41.87 GJ

Note: Kilo (k) = 10^3; mega (M) = 10^6; giga (G) = 10^9.

at a certain rate. The term "power" expresses the rate at which work is done or energy is expended. The basic unit of power is the watt (W), which equals 1 joule/s, 14.3 kcal/min, or 3.41 Btu/h. Another unit of power commonly used is the horsepower (HP); 1 HP equals 746 W or 2542 Btu/h.

When the power level, or rate at which work is done, is multiplied by the time the work requires, we obtain the total flow of energy. For instance, the maximum work capacity or power level that a horse can sustain for a 10-h working day is 1 HP. The power level of a person is about one-tenth of 1 HP; therefore, a person working a 10-h day produces an energy equivalent of only 1 HPh (horsepower hour), 2.7 MJ (megajoules), or 0.75 kWh. Put another way, one horse can accomplish the same amount of work as 10 people in 1 h. Horsepower and oxpower were some of the first substitutes for human power and contributed to improving the quality of human life. Certainly people tilling the soil in early agriculture were more productive when they used oxen and horses.

The tremendous effect of technological development on human activities can be appreciated by comparing human power to the mechanical power of a tractor fueled with gasoline. One gallon (3.79 L) of gasoline contains about 31,000 kcal of potential energy. When this gallon of gasoline fuels a mechanical engine, which is about 20% efficient in converting heat energy into mechanical energy, an equivalent of 8.8 kWh of work can be achieved. Hence, a single gallon of gasoline produces more power than a horse working at maximum capacity for 10 h (7.5 kWh). Further, 1 gallon of gasoline produces the equivalent of almost 3 weeks of human work at a rate of 0.1 HP, or 0.075 kW, for 40 h a week.

BIOLOGICAL SOLAR ENERGY CONVERSION IN AGRICULTURE

The survival of humans in their ecosystem depends upon the efficiency of green plants as energy converters. Plants convert sunlight into food energy for themselves and other organisms. The total foundation of life rests on plants' unique capacity to change radiated solar energy into stored chemical energy that is biologically useful for humans and other animals.

The amount of solar energy reaching 1 hectare (ha) each day in the temperate region ranges from 15 to 40 million kcal. Over a year's time, the total solar energy received per ha ranges from 1.1 to 1.8×10^{10} kcal, with 1.4×10^{10} kcal as a reliable average. This is equivalent to the energy potential of nearly 452,000 gal (1.7 million liters) of gasoline per year per hectare. This sounds like a large quantity of energy, and indeed it is when considered as a unit. But each square millimeter (mm) receives only 0.0038 kcal per day, only enough to raise the temperature of 3.8 mL of water 1°C.

Green plants are able to capture only a small percentage (0.1%) of the sunlight reaching the Earth (Whittaker and Likens, 1975; ERAB, 1981). Annually, the total light energy fixed by green plants in ecosystems is estimated to be about 400×10^{15} kcal, divided equally between terrestrial and ocean ecosystems (Pimentel et al., 1978). Note that although terrestrial systems cover only about a third of the Earth, the plants in these systems fix about half of the total light energy captured.

When only the temperate zone is considered, estimates are that only 0.07% of the 1.4×10^{10} kcal of sunlight per hectare is fixed in terrestrial ecosystems (Reifsnyder and

Lull, 1965). Thus, the net energy fixed by plants in the temperate zone averages about 10 million kcal/ha per year. Expressed as dry weight of plant material, this amounts to an average yield of 2400 kg/ha per year, ranging from near zero in some rock and desert areas to 10,000 kg/ha in some swamps and marshes (Whittaker and Likens, 1975).

In agricultural ecosystems, an estimated 15 million kcal of solar energy (net production) is fixed per ha per crop season. Even so, this amounts to only about 0.1% of the total solar energy reaching each hectare during the year and equals about 3500 kg/ha of dry biomass. The amount of biomass varies with the crop and ranges from 200 kg/ha for low-production crops under arid conditions to 18,000 kg/ha for corn and sugarcane. An average agricultural ecosystem produces an annual biomass per hectare slightly greater than that in natural ecosystems. This is not surprising as crop plants are grown on the most fertile soils and are usually provided with ample moisture and essential nutrients. Under optimal conditions, during sunny days in midsummer and when the plants are nearing maturity, crops such as corn and sugarcane capture as much as 5% of the sunlight energy reaching them. However, the harvested plant material is only about 0.1% because over much of the year, including winter, there is no plant growth.

A significant quantity of captured energy is, of course, utilized by the plant itself. For example, a soybean plant uses about 25% of the energy it collects for its own respiration and maintenance. About 5% of the energy is diverted to provide food for the nitrogen-fixing bacteria that are symbionts with the soybean plant. Another 10% is lost to insect pests and pathogens that feed on the plant. Thus, the net yield in beans plus vegetation is about 60% of the energy collected by the plant.

Most plants divert significant proportions—from 5% to 50%—of the energy they collect into their fruits and seeds, illustrating the high priority plants give to reproduction (Harper, 1977).

Humans have used breeding techniques to reallocate energy in plants and improve crop yields. For example, one of the factors contributing to the increased yields in new breeds of corn has been the change in energy allocation within the plant. In particular, the new breeds produce smaller tassels and less pollen, and the energy saved is reallocated to the production of corn grain. With corn plants, growing as densely as they do under normal cropping conditions, the smaller tassel and less abundant pollen are satisfactory for the production of corn seed.

RENEWABLE BIOLOGICAL ENERGY VERSUS FOSSIL FUEL ENERGY

By the sixteenth century, England and France were running out of firewood, their most important source of renewable biomass (Nef, 1977). Humans used wood to cook and prepare foods and to heat the homes of the expanding population. They also used it to produce charcoal for the developing metal industry and to provide lumber for the growing shipbuilding and construction industries. Owing to the shortage of wood, London and Paris were forced to turn to soft coal as a substitute fuel (Cook, 1976). As soft coal is noxious when burned, wood remained the preferred fuel; and those who could afford its high price continued to burn wood. During the eighteenth century, coal was used primarily for heating; its use as a source of energy to replace human and horsepower did not occur until the nineteenth century.

Coal was used extensively, however, to fuel pumps in mining operations. As mines were dug deeper, water began seeping into the mines and caused serious flooding problems. The mine operators used windmills, hand pumps, and windlasses to remove water, but with poor results. Then, in 1698, Thomas Savery invented the first steam-powered pump to remove water from the mines. This pump, however, proved dangerous to operate and was never fully adopted. About 10 years later, Thomas Newcomen designed a much improved steam-powered pump that was extensively employed in the mines. Thereafter coal could be mined more efficiently, and a good supply was ready to replace the declining supply of firewood. It was not until nearly 100 years later that James Watt designed a truly efficient steam engine and pump. When the Watt pump was finally operational, it rapidly replaced the Newcomen steam pump.

The Watt steam engine and the internal combustion engine, developed in 1876, brought dramatic changes in energy consumption. These new fossil fuel-powered engines quickly replaced the less efficient wood-powered steam engines, the horse, and even human power. Production of goods increased, expenditure of energy increased, and each subsequent decade witnessed a further increase in the use of nonrenewable fuel resources.

In the United States, from 1700 to 1800, wood was the primary source of fuel. As late as 1850, more than 91% of the energy used in the United States came from wood burning (EOP, 1977). The supply of wood was sufficient in the eighteenth and early nineteenth centuries for two reasons. Not only was the population about 23 million people, or less than 8% the present level, but these early settlers consumed only about one-fifth the amount of energy consumed today. Furthermore, American forests had been harvested for only a relatively short period of time compared to European forests. Even so, as early as 1850 firewood was in short supply in the Northeast, especially for larger cities such as New York and Boston, because of the rapid clearing of forestland for agricultural production and the relatively heavy demand for firewood. The problem was worsened by the difficulty and high costs of transporting the bulky and heavy wood over increasingly long distances to the cities.

Obviously, forests cannot meet the high energy needs of today's large U.S. population. At present, fossil fuels account for 94% of the total fuel consumption in the United States. Of this, oil represents 40%, natural gas 28%, coal 26%, and nuclear fuels 6%. Firewood accounts for only 4% and hydroelectric energy the remaining 3.5% of the total fuel. Fossil fuel consumption today is the highest it has ever been. Annual consumption for the world stands at about 473 quads (119×10^{15} kcal) and is increasing every year. The United States alone consumes 25% of all the fossil energy used in the world annually, amounting to 103 quads (26×10^{15} kcal).

The epoch of fossil fuel use has been but a short interval in the more than 1 million years of human existence on Earth (Figure 2.1). The era of reliance on fossil fuels will be but a small "blip" in history—about 400 years, or at most 0.1% of the time humans have been on Earth. As fossil fuels are nonrenewable resources, they eventually will be exhausted. Oil and gas supplies will be the first fossil fuels to run out. According to the best estimates, 30 to 50 years of these resources remain. The United States has only 10 to 20 years of oil reserves remaining based on current use rates.

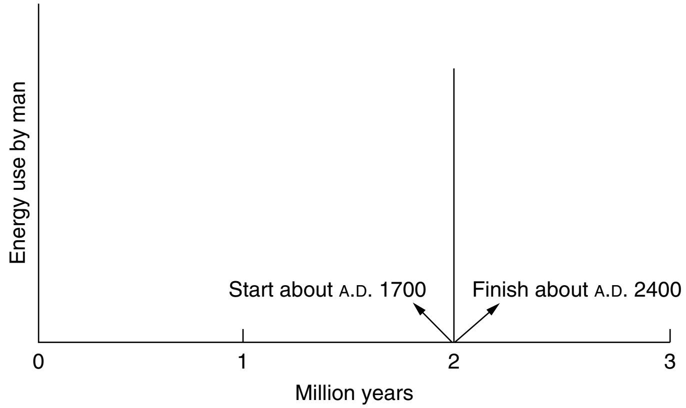

FIGURE 2.1 The epoch of the use of fossil fuels in the history of man on Earth.

U.S. oil imports now amount to 63% of the country's total use, and this share is expected to increase to about 70% by the turn of the century. Most of the European countries, Japan, and several other countries in the world import *all* of their oil, which places a strain on their economies.

The world's coal reserves are greater than those of oil and gas because the latter fuels have been more extensively used than coal. There is still an estimated 100-year supply of coal in the world (Hubbert, 1972; Matare, 1989; Worldwatch Institute, 1992). However, continued heavy use of fossil fuels may cause grave problems relating to global climate change (Schneider, 1989). In addition, the burning of fossil fuels results in major air pollution problems, and coal mining, especially strip mining, damages the environment, destroying vast areas of land valued for food and forest production and wildlife. On average, strip mining is safer for miners, is more economical, and requires less energy than deep underground mining, and it is 80% to 90% effective in recovering coal, whereas deep mining is only 50% effective. In deep mining, small coal seams cannot be economically mined because of the danger of cave-ins.

Coal production requires less energy than oil drilling both in extraction and transportation. About 20% of the potential energy in oil is expended to extract and refine it (Cervinka, 1980), resulting in a yield of about 80% at point of use. By comparison, coal has a yield of about 92% (Cook, 1976). This means that about 108 kg of coal must be mined to produce the equivalent of 100 kg of coal energy, compared with 112 kg of oil pumped for 100 kg of oil energy.

Coal reserves are scattered throughout the world. Western Europe has about 5% of the total, the United States about 20%. Russia is extremely well endowed, with nearly 56% of the estimated coal reserves.

Adjusting from oil and gas to coal will require many changes in lifestyle and industrial production methods. The world is indeed fortunate to have coal reserves as a backup energy resource until renewable energy technologies are developed to supply a portion of the world's energy needs.

REFERENCES

Cervinka, V. 1980. Fuel and energy efficiency. In D. Pimentel (ed.), *Handbook of Energy Utilization in Agriculture*, pp. 15–24. Boca Raton, FL: CRC Press.

Cook, E. 1976. *Man, Energy, Society*. San Francisco, CA: W.H. Freeman.

Energy Research Advisory Board (ERAB). 1981. *Biomass Energy*. Washington, D.C.: ERAB, U.S. Department of Energy.

Executive Office of the President (EOP). 1977. *The National Energy Plan*. Washington, D.C.: Executive Office of the President, Energy Policy and Planning.

Harper, J.L. 1977. *Population Biology of Plants*. London: Academic Press.

Hubbert, M.K. 1972. Man's conquest of energy: Its ecological and human consequences. In A.B. Kline (ed.), *The Environmental and Ecological Forum 1970–1971*, pp. 1–50. Oak Ridge, TN: U.S. Atomic Energy Commission Technical Information Center.

Matare, H.F. 1989. *Energy: Fact and Future*. Boca Raton, FL: CRC Press.

Nef, J.V. 1977. An early energy crisis and its consequences. *Scientific American* 237: 140–151.

Pimentel, D., D. Nafus, W. Vergara, et al. 1978. Biological solar energy conversion and U.S. energy policy. *BioScience* 28: 376–382.

Reifsnyder, W.E. and H.W. Lull. 1965. Radiant energy in relation to forests. Technical Bulletin No. 1344. Washington, D.C.: U.S. Department of Agriculture, Forest Service.

Schneider, S.H. 1989. *Global Warming: Entering the Greenhouse Century*. San Francisco, CA: Sierra Club Books.

Steinhart, C. and J. Steinhart. 1974. *Energy Sources, Use and Role in Human Affairs*. North Scituate, MA: Duxbury Press.

Whittaker, R.H. and G.E. Likens. 1975. The biosphere and man. In H. Lieth and R.H. Whittaker (eds.), *Primary Productivity of the Biosphere*, pp. 305–328. New York: Springer-Verlag.

Worldwatch Institute. 1992. *State of the World 1992*. Washington, D.C.: Worldwatch Institute.

3 Solar Energy in Natural and Managed Ecosystems

Natural ecosystems, of which humans are a part, are fundamentally a network of solar energy and mineral flows. Green plants capture solar energy and convert it into chemical energy for use by themselves and the remainder of the biological system using the elements of carbon, hydrogen, oxygen, nitrogen, phosphorus, potassium, calcium, magnesium, and others. The food supplied by plants in the ecosystem is basic to the survival of all animals, including humans. It is the foundation of the entire life system. Some of the solar energy plants convert into stored chemical energy is passed on to herbivores and parasitic microbes. The success of agriculture and forestry is measured by the amount of solar energy captured as biomass in crops and forests. The biomass yield depends on the manipulation of these plants—which need fertile soil, water, and a favorable climate—using human, animal, and fossil fuel power for tilling, planting, weed control, harvesting, and various other activities.

In this chapter, we focus on solar energy as a fundamental resource for the functioning of both natural and managed ecosystems. Also considered are the limitations of solar energy and the land area of the terrestrial ecosystems in the United States.

NATURAL ECOSYSTEMS

The solar energy reaching a hectare of land in temperate North America averages about 14 billion kcal per year (Reifsnyder and Lull, 1965). This is the equivalent of the energy contained in about 1.4 million liters (370,000 gal) of oil, or the energy used by 133 Americans for 1 year. However, most plants in the temperate zone of the United States do not grow during the winter months, achieving most of their growth during a relatively short 4-month summer. During this period, nearly 7 billion kcal—about half of the year's sunlight energy—reach each hectare of land.

Consider now how the solar energy is converted into biomass by vegetation. The total area in the United States, including lakes and rivers, is 1049 million ha. The total biomass produced annually is 2793 million tons, or nearly 3 tons/ha (Table 3.1). If we assume 4200 kcal per kg of biomass, then the total energy captured is 11.7 million kcal/ha per year, or slightly less than 0.1% of the total sunlight energy reaching each hectare.

Although in the tropics there are no winters, there are dry periods during which little plant biomass is produced. Thus, biomass productivity in the tropics, on average, is quite similar to that of temperate regions. In the tropics, the prime limiting factor is moisture, whereas in the temperate United States temperature is the prime limiting factor.

TABLE 3.1
Total Annual Plant Biomass Production in the United States

Location	Area (million ha)	Biomass (dry tons/ha)	Total Biomass (dry Mt)[a]
Terrestrial farmland			
Cropland	135	6	810
Cropland idle	21	4	84
Cropland in pasture	36	4	144
Grassland in pasture	183	2	366
Forest and woodland	45	3	135
Farmsteads, roads	11	0.1	1
Other			
Grazing land	117	2	234
Forest land	202	3	606
Other land, urban, marshes, desert	167	0.1	17
Subtotal	917	—	2397
Aquatic			
Lakes and rivers	132	3	396
Total	1049	—	2793

[a] Mt = million metric tons.

In natural ecosystems, the approximately 3 tons/ha/year of biomass available limits the number of consumers and the number of links in the food chain. Usually only about 10% of the energy is passed on from one consumer level to the next. Therefore, rarely do links in the food chain number more than 4 or 5. This explains why some large predators, such as tigers, must range over hundreds of hectares to find adequate amounts of food. Thus, energy, along with moisture and nutrients (nitrogen, phosphorus, potassium, etc.), is a major limiting factor for natural ecosystems.

Plants in the United States fix about 13.5×10^{15} kcal of solar energy per year (Figure 3.1), which is significantly less than the current annual fossil energy consumption of about 20×10^{15} kcal. Indeed, Americans burn about 40% more fossil energy than the total solar energy captured by all the plant biomass in the United States each year (Figure 3.1). These figures illustrate that humans' use of fossil energy is far out of balance with the energy naturally available and renewable in their ecosystem. In addition, fossil energy has made drastic changes in the U.S. ecosystem, including the removal of forests and natural prairies.

About 70% of the total energy fixed in the terrestrial United States is produced on agricultural lands, the remainder from plants growing on nonagricultural lands (Table 3.1). Any analysis of the effectiveness of biological solar energy conversion in nature and managed ecosystems must consider agricultural and forestry production. About 70% of the U.S. land area is used for food and forest production (Table 3.1). Each year the total amount of solar energy harvested annually in the form of agricultural crops and forestry products is about 6.9×10^{15} kcal (5.8×10^{15} kcal net

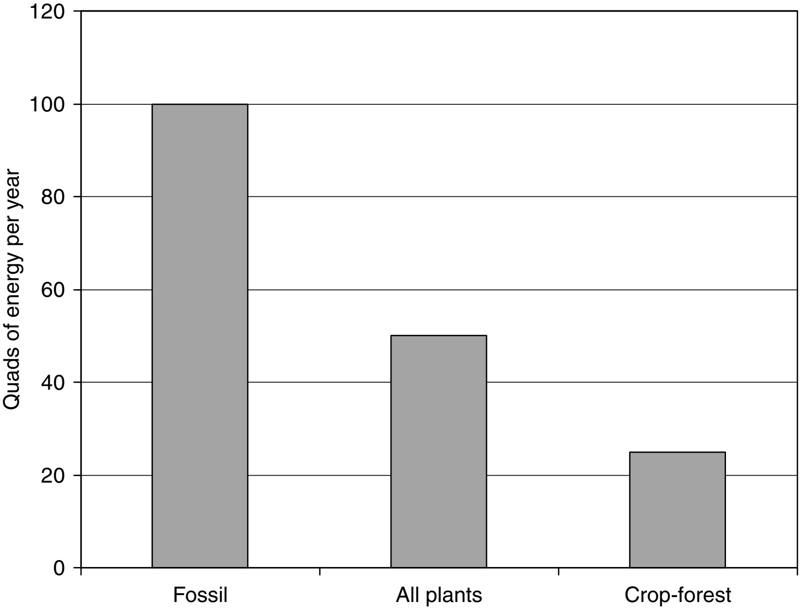

FIGURE 3.1 The solar energy captured annually in the United States compared with fossil energy consumption and the amount of solar energy harvested as crop and forest products.

energy). This represents about 30% of the fossil energy consumption in the United States. Pasture and other forage crops account for about 66% of the harvested energy, whereas food crops total 16% and forest products 18%.

The 6.9 × 10^{15} kcal of biological energy harvested in the form of agricultural and forestry products has several significant implications. First, about half of all the solar energy fixed by plants in the United States is harvested and used by humans and livestock, whereas the other half is used within the natural ecosystem. Thus, the energy produced in both agriculture/forestry and the natural ecosystem is vital to the functioning of the human economy and sustains the health of the natural environment. This conclusion suggests that Americans are making maximal use of the land to produce biomass for food and forest products and that their natural ecosystem also requires a large amount of biomass to maintain it. Furthermore, the use of biomass as fuel must be limited, because food and forest biomass support the diverse needs and activities of human society.

FOREST ECOSYSTEMS

Net primary production in U.S. forests is about 3 tons/ha/year (Table 3.1). This yield is slightly more than the average net primary production for all the ecosystems in the nation. It includes leaves and small twigs, so the net harvest of biomass wood is, optimistically, about 2 tons/ha, which provides about 8.4 million kcal of energy when burned to produce heat energy. Each American consumes the equivalent of 81 million kcal in fossil fuel annually, or the energy produced from about 10 ha of forest.

AGRICULTURAL ECOSYSTEMS

Annual net primary production in U.S. agricultural ecosystems is about 5 tons/ha (Table 3.1). This figure is higher than the overall average yield of biomass per hectare because crops are grown under favorable conditions regarding moisture, soil nutrients, and soil quality. For example, corn grown under favorable conditions will produce 9 tons/ha of corn grain, plus an additional 9 tons/ha of stover. Converted into heat energy, this totals about 66×10^6 kcal per ha. This represents about 0.5% of the solar energy reaching 1 ha during the year, a relatively high rate of conversion for crops and natural vegetation. Most crops have about a 0.1% level of conversion.

In summary, the terrestrial ecosystem is extremely important to the survival of humans because more than 99% of their food and 100% of their forest products comes from terrestrial plants that capture solar energy. In addition, the terrestrial ecosystem, in capturing solar energy, helps maintain the natural ecosystem and a quality environment.

REFERENCE

Reifsnyder, W.E. and H.W. Lull. 1965. Radiant energy in relation to forests. Technical Bulletin No. 1344. Washington, D.C.: U.S. Department of Agriculture, Forest Service.

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

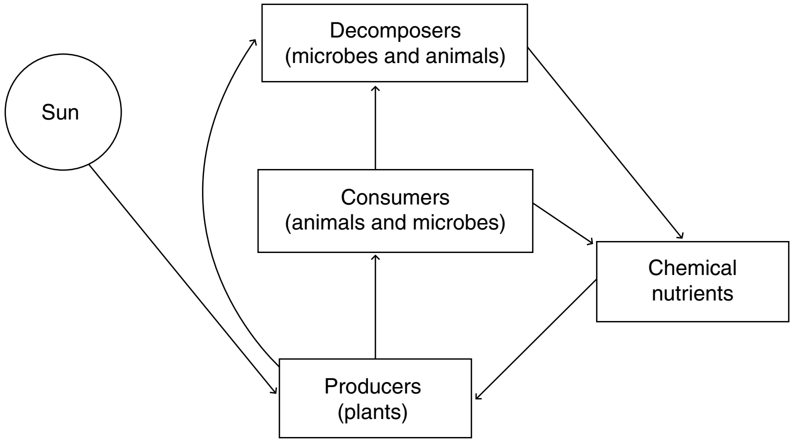

FIGURE 4.1 Structure of living systems.

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

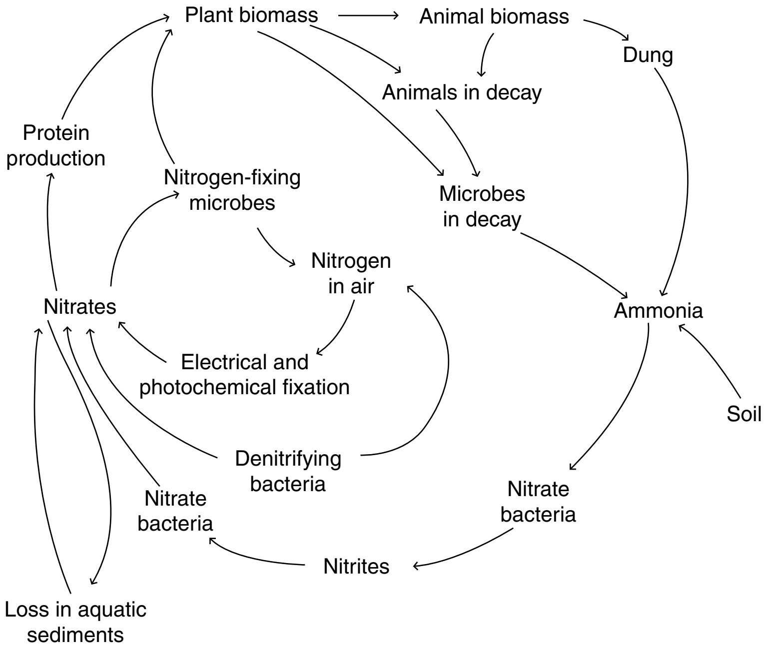

FIGURE 4.2 The nitrogen biogeochemical cycle.

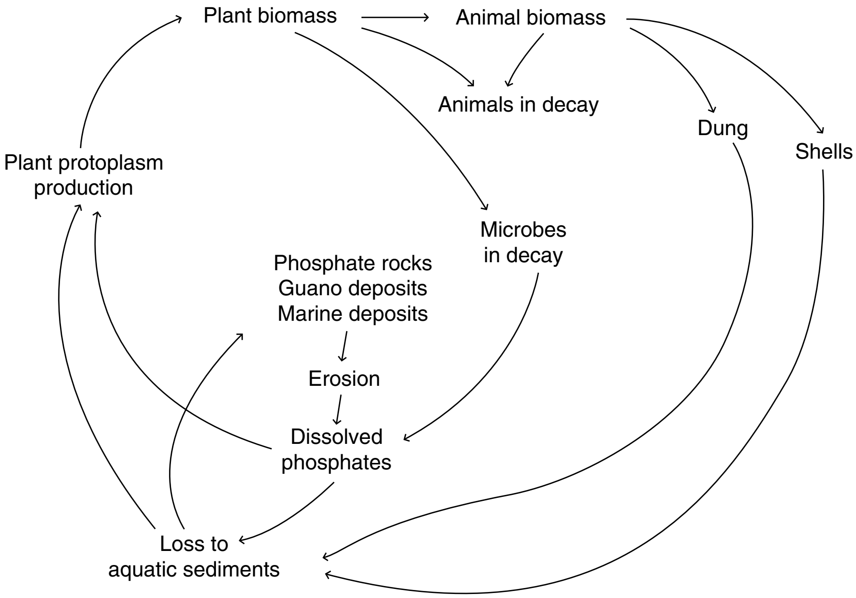

FIGURE 4.3 The phosphorus biogeochemical cycle.

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

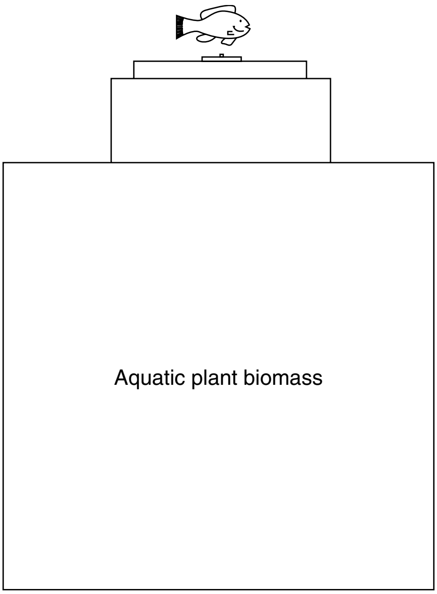

FIGURE 4.4 Trophic pyramid in an aquatic ecosystem indicating the small quantity of fish that might be harvested from the relatively large quantity of aquatic plant biomass.

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.

REFERENCES

Allee, W.C., A.E. Emerson, O. Park, et al. 1949. *Principles of Animal Ecology*. Philadelphia, PA: Saunders.

Allison, F.E. 1973. *Soil Organic Matter and Its Role in Crop Production*. New York: Elsevier.

Andrewartha, H.G. and L.C. Birch. 1954. *Distribution and Abundance of Animals*. Chicago, IL: University of Chicago Press.

Berryman, A.A. 1982. Population dynamics of bark beetles. In J.B. Mitton and K.B. Sturgeon (eds.), *Bark Beetles in North American Conifers. A System for the Study of Evolutionary Biology*, pp. 264–314. Austin, TX: University of Texas Press.

Campbell, R.W. 1974. The gypsy moth and its natural enemies. *Forest Service Agriculture Information Bulletin* 381. Washington, D.C.: U.S. Department of Agriculture.

Campbell, R.W. and J.D. Podgwaite. 1971. The disease complex of the gypsy moth. I. Major components. *Journal of Invertebrate Pathology* 28: 101–107.

Cates, R.G. 1975. The interface between slugs and wild ginger: Some evolutionary aspects. *Ecology* 56: 391–400.

Coley, P.D., J.P. Ryant, and F.S. Chapin. 1985. Resource availability and plant antiherbivore defense. *Science* 230: 895–899.

Delwiche, C.C. 1970. The nitrogen cycle. *Scientific American* 223: 137–158.

de Mesa, A. 1928. The Insect Oak-Galls in the Vicinity of Ithaca. Thesis. Ithaca, NY: Cornell University Press.

Ehrlich, P. and A. Ehrlich. 1990. *The Population Explosion*. New York: Simon and Schuster.

Elton, C.S. 1927. *Animal Ecology*. London: Sidgwick and Jackson, Ltd.

Food and Agriculture Organization (FAO). 1961–2004. Food balance sheets. Rome: Food and Agriculture Organization of the United Nations.

Food and Agriculture Organization (FAO). 2002. Food balance sheets. Rome: Food and Agriculture Organization of the United Nations.

Hairston, N.G., F.E. Smith, and L.B. Slobodkin. 1960. Community structure, population control and competition. *American Naturalist* 94: 421–425.

Humphreys, W.F. 1979. Production and respiration in animal populations. *Journal of Animal Ecology* 48: 427–454.

Jones, D.A. 1966. On the polymorphism of cyanogenesis in *Lotus corniculatus*. Selection by animals. *Canadian Journal of Genetics Cytology* 8: 556–567.

Jones, D.A. 1979. Chemical defense: Primary or secondary function? *American Nature* 113: 445–451.

Krischik, V.A. and R.F. Denno. 1983. Individual, population, and geographic patterns of plant defense. In R.F. Denno and M.S. McClure (eds.), *Variable Plants and Herbivores in Natural and Managed Systems*, pp. 463–512. New York: Academic Press.

Lawton, J.H. and S. McNeil. 1979. Between the devil and the deep blue sea: One problem of being a herbivore. In R.M. Anderson, B.D. Turner, and L.R. Taylor (eds.), *Population Dynamics*, pp. 223–244. Oxford: Blackwell.

Leonard, D.E. 1974. Recent developments in ecology and control of the gypsy moth. *Annual Review of Entomology* 19: 197–229.

Levin, D.A. 1976. The chemical defenses of plants to pathogens and herbivores. *Review of Ecology and Systematics* 7: 121–159.

Levin, S. and D. Pimentel. 1981. Selection of intermediate rates of increase in parasite-host systems. *American Naturalist* 117: 308–315.

Martin, J.P., E.V. Abbott, and C.C. Hughes. 1961. *Sugar-cane Diseases of the World.* Amsterdam: Elsevier.

McKey, D. 1974. Adaptive patterns in alkaloid physiology. *American Naturalist* 108: 305–320.

McNeil, S. and J.H. Lawton. 1970. Annual production and respiration in animal populations. *Nature (London)* 225: 472–474.

National Academy of Sciences (NAS). 1977. *World Food and Nutrition Study.* Washington, D.C.: National Academy of Sciences.

National Academy of Sciences (NAS). 2003. *Frontiers in Agricultural Research: Food, Health, Environment, and Communities.* Washington, D.C.: National Academies of Science.

Nichols, J.O. 1961. *The Gypsy Moth in Pennsylvania—Its History and Eradication.* Harrisburg, PA: Pennsylvania Department of Agriculture Miscellaneous Bulletin 4404.

Odum, E.P. 1971. *Fundamentals of Ecology.* Philadelphia, PA: W.B. Saunders Co.

Odum, E.P. 1978. *Fundamentals of Ecology.* New York: Saunders.

Opler, P.A. 1974. *Biology, Ecology, and Host Specificity of Microlepidoptera Associated with* Quercus agrifolia (Fagacceae). Berkeley: University of California Press.

Packard, A.S. 1890. *Insects Injurious to Forest and Shade Trees.* Washington, D.C.: USDA Forest Service.

Phillipson, J. 1966. *Ecological Energetics.* London: Arnold.

Pimentel, D. 1961. Animal population regulation by the genetic feedback mechanism. *American Nature* 95: 65–79.

Pimentel, D. 1968. Population regulation and genetic feedback. *Science* 159: 1432–1437.

Pimentel, D. 1977. Ecological basis of insect pest, pathogen and weed problems. In J.M. Cherrett and G.R. Sagar (eds.), *The Origins of Pest, Parasite, Disease and Weed Problems*, pp. 3–31. Oxford: Blackwell.

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

Pimentel, D. (ed.). 1991. *Handbook of Pest Management in Agriculture.* 3 volumes. Boca Raton, FL: CRC Press.

Pimentel, D. (ed.). 1993. *World Soil Erosion and Conservation.* Cambridge, UK: Cambridge University Press.

Pimentel, D. and C.W. Hall (eds.). 1989. *Food and Natural Resources.* San Diego: Academic Press.

Pimentel, D. and D. Wen. 1990. Technological changes in energy use in U.S. agricultural production. In C.R. Carrol, J.H. Vandermeer, and P.M. Rosset (eds.), *Agroecology*, pp. 147–164. New York: McGraw Hill.

Pimentel, D. and M. Pimentel. 2003. World population, food, natural resources, and survival. *World Futures* 59(3–4): 145–167.

Pimentel, D., S.A. Levin, and A.B. Soans. 1975. On the evolution of energy balance in exploiter–victim systems. *Ecology* 56: 381–390.

Pimentel, D., W. Jackson, M. Bender, et al. 1986. Perennial grains: An ecology of new crops. *Interdisciplinary Science Review* 11: 42–49.

Pimentel, D., J. Allen, A. Beers, et al. 1987. World agriculture and soil erosion. *BioScience* 37: 277–283.

Pimentel, D., L. McLaughlin, A. Zepp, et al. 1993. Environmental and economic impacts of reducing U.S agricultural pesticide use. *Agriculture, Ecosystems and Environment* 46(1–4): 273–288.

Pimentel, D., C. Harvey, P. Resosudarmo, et al. 1995. Environmental and economic costs of soil erosion and conservation benefits. *Science* 267: 1117–1123.

Podgwaite, J.D. and R.W. Campbell. 1972. The disease complex of the gypsy moth. II. Aerobic bacterial pathogens. *Journal of Invertebrate Pathology* 20: 303–308.

Price, P.W. 1975. *Evolutionary Strategies of Parasitic Insects and Mites*. New York: Plenum.

Price, P.W., C.E. Bouton, P. Gross, et al. 1980. Interactions among three trophic levels: Influence of plants on interactions between insect herbivores and natural enemies. *Annual Review of Ecology and Systematics* 11: 41–65.

PSAC. 1965. *Restoring the Quality of Our Environment*. Report of the Environmental Pollution Panel, November. Washington, D.C.: President's Science Advisory Committee.

Reifsnyder, W.E. and H.W. Lull. 1965. Radiant energy in relation to forests. Technical Bulletin No. 1344. Washington, D.C.: U.S. Department of Agriculture, Forest Service.

Rhoades, D.F. 1985. Offensive-defensive interactions between herbivores and plants: Their relevance in herbivore population dynamics and ecological theory. *American Naturalist* 125: 205–238.

Rosenthal, G.A. 1986. The chemical defenses of higher plants. *Scientific American* 254: 76–81.

Schroder, H. 1985. Nitrogen losses from Danish agriculture—Trends and consequences. *Agriculture Ecosystems and Environments* 14: 279–289.

Schultz, J.C. 1983a. Habitat selection and foraging tactics of caterpillars in heterogenous trees. In R.F. Denno and M.S. McClure (eds.), *Variable Plants and Herbivores in Natural and Managed Systems*, pp. 61–90. New York: Academic Press.

Schultz, J.C. 1983b. Impact of variable plant defensive chemistry on susceptibility of insects to natural enemies. In P. Hedin (ed.), *Plant Resistance to Insects*, pp. 37–54. Washington, D.C.: American Chemical Society.

Segal, A., J. Manisterski, G. Fishbeck, et al. 1980. How plant populations defend themselves in natural ecosystems. In J.G. Horsfall and E.B. Cowling (eds.), *Plant Disease*, pp. 75–102. New York: Academic Press.

Slobodkin, L.B. 1960. Ecological energy relationships at the population level. *American Naturalist* 94: 213–236.

Strong, D.R., E.D. McCoy, and J.D. Rey. 1977. Time and number of herbivore species: the pests of sugarcane. *Ecology* 58: 167–175.

Troeh, F.R. and L.M. Thompson. 1993. *Soils and Soil Fertility*. 4th ed. New York: McGraw-Hill.

Vanderholm, D.H. 1975. Nutrient losses from livestock waste during storage, treatment and handling. In *Managing Livestock Waste*, pp. 282–285. St. Joseph, MI: American Society of Agricultural Engineers.

Volk, B. and G. Loeppert. 1982. Soil organic matter. In V.J. Kilmer (ed.), *Handbook of Soils and Climate in Agriculture*, pp. 211–268. Boca Raton, FL: CRC Press.

Webb, M. and J. Jacobsen. 1982. *U.S. Carrying Capacity. An Introduction*. Washington, D.C.: Carrying Capacity Network.

Whittaker, R.H. and P.P. Feeny. 1970. Allelochemicals: Chemical interactions between species. *Science* 171: 757–770.

Wilson, E.O. (ed.). 1988. *Biodiversity*. Washington, D.C.: National Academy Press.

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.

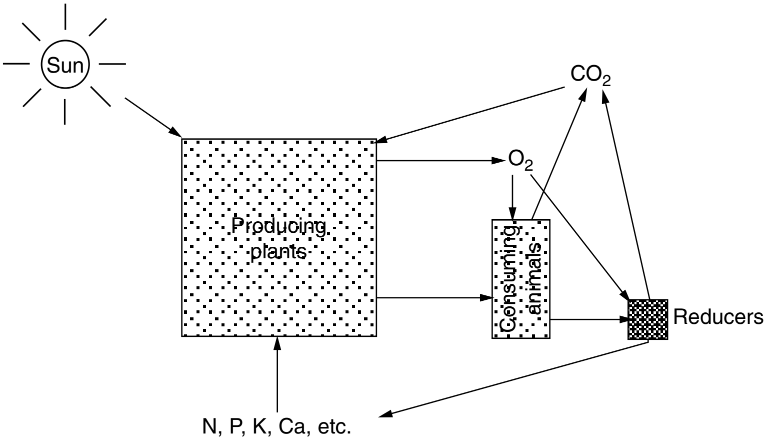

FIGURE 5.1 Producing plant-fixed solar energy that is consumed by animals, and that are in turn consumed by the reducers. The quantity of energy transferred is schematically diagrammed. Recycling of some of the mineral resources is illustrated.

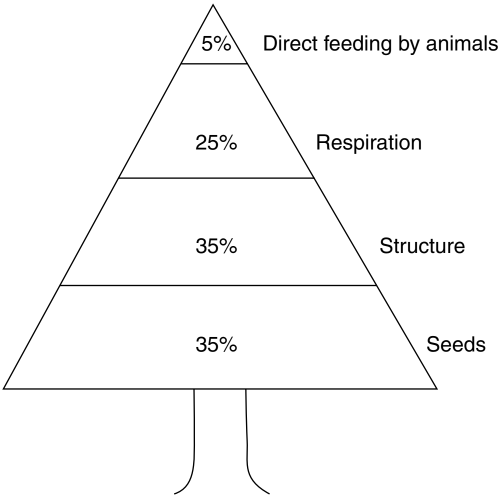

FIGURE 5.2 Of the solar energy fixed by crop plants, about 25% is used for respiration, 35% for building and maintaining the plant structure, and 35% for reproduction (seeds). The energy removed by direct feeding is estimated to be about 5%.

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

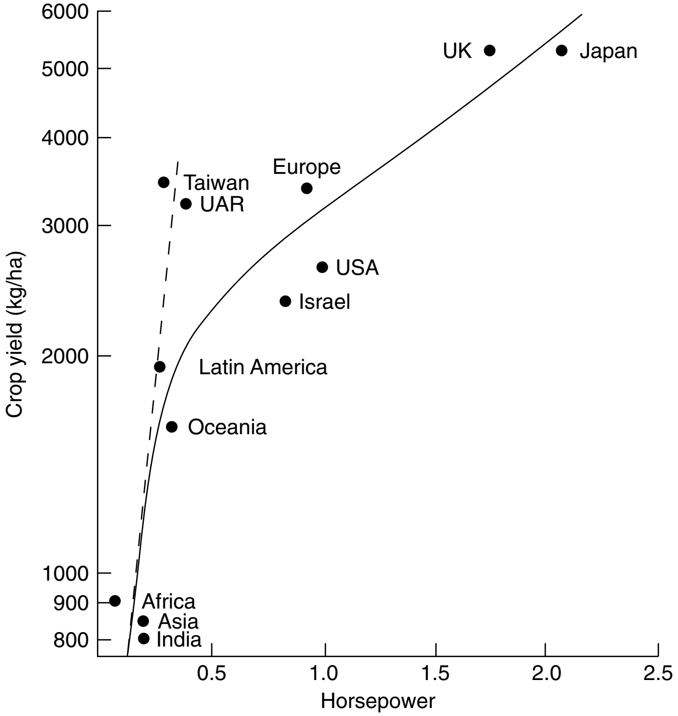

FIGURE 5.3 Relationship between crop yields per hectare of cereals, pulses, oil-seeds, sugar crops, potatoes, cassava, onions, and tomatoes, on the one hand, and horsepower per hectare, on the other, in various countries and regions (Asia excludes China). (From Blaxter, K., *Farmer's Weekly*, January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

6 Hunter-Gatherers and Early Agriculture

Before the development of agriculture and formal crop culture, wild plants and animals in the natural ecosystem were the only food for humans. How much wild plant and animal biomass is available for food, and how much land do hunter-gatherers need to meet their food needs?

The total annual production of plant biomass in the temperate region averages about 2400 kg (dry)/hectare. Under favorable conditions, this quantity of plant biomass might support an animal and microbe biomass of about 200 kg/ha (dry)/year. The proportions of the total 200 kg that comprise microbes, earthworms, arthropods, mammals, birds, and other animals are indicated in Figure 6.1.

Let us assume that a hunter-gatherer required 2500 kcal/day to meet his or her energy needs. By harvesting 0.1% of the available animal biomass from 40 ha, he or she would be able to consume 88 kcal/day (32,000 kcal/year) in the form of animal protein. The remaining 2412 kcal/day (880,500 kcal/year) of needed food energy would come from other sources, including seeds, nuts, fruits, roots, and other plant foods. Assuming that 1 kg of digestible plant material yields 3000 kcal, the hunter-gatherer would have to harvest about 300 kg of plant material from 40 ha (7.5 kg/ha/year) to meet calorie needs. Although obtaining this amount of plant material suitable for food might not be possible in a heavily wooded habitat, it likely would be possible on land containing a mixture of wood, shrubs, and herbs, as well as a productive stream.

If the plant food gathered contained an average of 5% protein, then a total of 12.2 kg of protein could be harvested per year, or about 34 g of plant protein per day. Combining the 34 g of plant protein and the 22 g of animal protein, the hunter-gatherer's diet would include a total of 56 g of protein per day under optimal conditions. The remaining calories would come from plant carbohydrates. Note that the consumption of fat was omitted from these calculations. Fats yielding 9 kcal/g would add substantially more calories to the daily intake. Except for animal flesh and such plant foods as nuts, the fat content of this diet would undoubtedly be lower than that of most diets consumed in the world today. Based on the preceding calculations, a family of five would require an estimated 200 ha of habitat from which to gather animal and plant food.

This estimate is based on an ideal ecosystem, one containing those wild plants and animals that are most suitable for human consumption. Researchers report that, in fact, modern-day hunter-gatherers need much more than 40 ha per person. For instance, Clark and Haswell (1970) estimate that at least 150 ha of favorable habitat per person is needed to secure an adequate food supply. In a moderately favorable

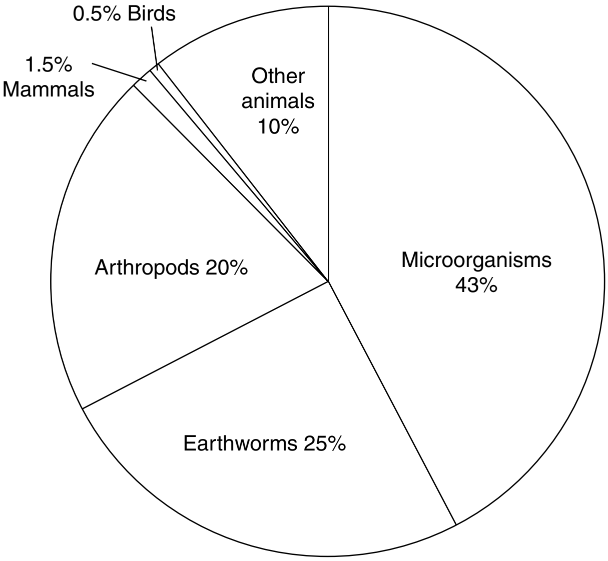

FIGURE 6.1 The proportion of the total biomass of 200 kg (dry) present in 1 ha that is made up of total animals and microorganisms biomass present in 1 ha.

habitat, these scientists estimate that 250 ha per person would be required. These estimates are four to six times greater than those in the model presented earlier.

In marginal environments, such as the cold northwestern Canadian region, each person needs about 14,000 ha to harvest about 912,500 kcal of food energy per year (Clark and Haswell, 1970). The land area may range as high as 50,000 ha per person in subarctic lands, and in these cold regions meat and animal products are the predominant foods in the diet. In fact, animal flesh and fat may constitute up to two-thirds of the food calories consumed.

Plant productivity in such marginal habitats may average only 10–200 kg/ha/year (Whittaker and Likens, 1975), and animal production may average only 1–4 kg/ha/year. The annual yield of meat for humans may average 5–10 g/ha of protein.

Assuming that two-thirds of human calorie intake in such a habitat comes from animal matter, humans could easily consume 77 g of animal protein per day. The plant products consumed might add another 35 g of protein, bringing the total protein intake per day to about 112 g. This is a high-protein diet, but it is not out of the range of population groups that eat high-protein diets today.

HUNTERS AND GATHERERS OF FOOD

Hunter-gatherers probably expend 60–80% of their energy intake in securing food. In fact, obtaining food and collecting firewood for its preparation usually dominate the activities of these societies.

As so much human energy is expended in searching for, collecting, and transporting food, let us consider the energy required by humans for these various

TABLE 6.1
Energy Requirements for Various Activities (kcal/h)

Light Work	kcal/h	Moderate Work	kcal/h
Sitting	19	Shoemaking	80–115
Writing	20	Sweeping	85–110
Standing relaxed	20	Dusting	110
Typing	16–40	Washing	125–215
Typing quickly	55	Charring	80–160
Sewing	30–90	Metal working	120–140
Dressing & undressing	33	Carpentering	150–190
Drawing	40–50	House painting	145–160
Lithography	40–50	Walking	130–240
Violin playing	40–50		
Tailoring	50–85		
Washing dishes	60		
Ironing	60		
Book binding	45–90		
Hard Work	**kcal/h**	**Very Hard Work**	**kcal/h**
Polishing	175	Stonemasonry	350
Joiner work	195	Sawing wood	420
Blacksmithing	275–350	Coal mining (average for shift)	800–1000
Riveting	275	Running	800–1000
Marching	280–400	Climbing	400–900
Cycling	180–600	Walking very quickly	570
Rowing	120–600	Rowing very quickly	1240
Swimming	200–700	Running very quickly	1240
		Walking upstairs	1000

Source: Pyke, M., *Man and Food*, McGraw-Hill, New York, 1970.

activities. The energy expended is above that used for daily basal metabolism, which is about 45 kcal/h or 1080 kcal/day (Pyke, 1970). Walking at a rate of about 4 km (2.5 miles) per hour uses an average of 180 kcal/h (Table 6.1). If the individual carries a load weighing from 9 to 23 kg while walking, the energy expended nearly doubles to about 340 kcal/h. Running at 11–13 km (7–8 miles) per hour uses 800 to 1000 kcal/h. If the hunter-gatherer has to walk or run several kilometers in pursuit of food, the energy expended in food procurement can be relatively large.

Some hunter-gatherer communities exist at a density of 1 person per 15,800 to 31,600 ha (Sahlins, 1972). If only two-thirds of such a population actively hunts and gathers, then each person must search up to 47,900 ha (185 square miles) per year for food. The remaining third of the population, consisting of young children and elderly, usually does little or no hunting and gathering.

If hunter-gatherers were to search 47,900 ha for food, covering 58 meter-wide swaths, then they would have to travel 8316 km per year to cover the entire area. This would require that a person walk 4 km/h for 40 h/week for 52 weeks/year. Obviously, this pace would test the endurance of the hardiest individual; early hunter-gatherers could not work at such a rate, nor can their present-day counterparts.

Hunter-gatherers do not have to search the total area for food. Because they know their territory well, they know approximately where to find food, greatly reducing the distances they have to travel in search of food. However, distant food locations, even if known, would require a long trip. For example, a journey from one side to the other of the hypothetical 47,900 ha area would cover about 22 km. A round trip across this area would require an expenditure of about 1980 kcal.

The !Kung bushmen, who presently inhabit the Dobe area of Botswana, Africa, illustrate the energy economy of a hunter-gatherer society (Lee, 1969; Lee and DeVore, 1976). The population studied consisted of 248 individuals and occupied an area of 2850 km^2. Each person required 10.4 km^2, or 1040 ha, for support. Note that this is much less land than the hunter-gatherers studied by Sahlins occupied—only 3% as much.

The habitat in which the !Kung bushmen live is relatively arid, with an annual rainfall of only 150–250 mm per year (Lee, 1969; Lee and DeVore, 1976; Marshall, 1976). Permanent watering holes, existing only in locations where the underlying limestone strata have been exposed, provide the only reliable supply of water. During the rainy season, water is also readily available at temporary water holes. A critical decision facing the bushmen is where to locate their camps. The location must allow them to obtain both food and water easily. Because water is the major limiting factor, the bushmen usually camp within easy reach of a reliable water source.

The food gathered by the bushmen consists, by weight, of 33% mongongo nuts, 37% meat, and 30% miscellaneous plant foods (Lee, 1969; Marshall, 1976). The nuts yield 1200 kcal/day, meat 768 kcal/day, and other plant foods 172 kcal/day, totaling a daily energy intake of 2140 kcal. This means that mongongo nuts contribute most (56%) of the daily calorie intake of the !Kung bushmen (Figure 6.2).

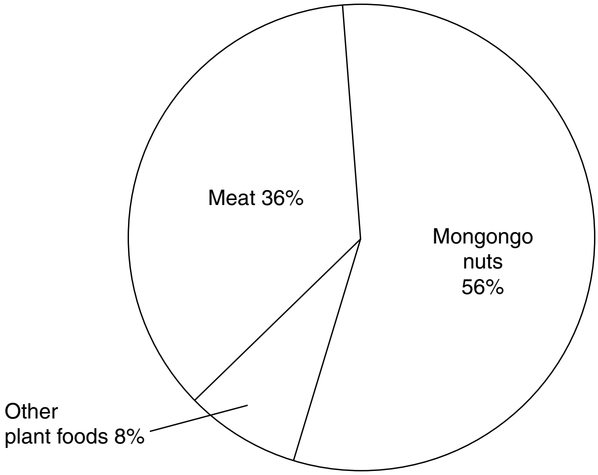

FIGURE 6.2 The percentage of various food types that make up the daily diet of the !Kung bushmen. (From Lee, R.B., *Environment and Cultural Behavior: Ecological Studies in Cultural Anthropology*, Natural History Press, New York, 1969.)

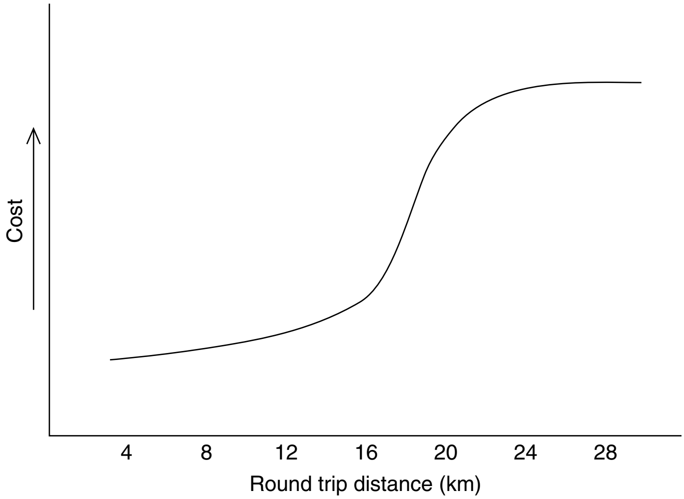

FIGURE 6.3 The energy cost of obtaining mongongo nuts at different distances. (After Lee, R.B., *Environment and Cultural Behavior: Ecological Studies in Cultural Anthropology*, Natural History Press, New York, 1969.)

As one might expect, the bushmen prefer to collect the desirable foods that are closest to a water supply. They occupy a camp for a period of weeks and literally eat their way out of it. For example, they often camp in the nut forests and "exhaust the nuts within a 1.6 km (1 mile) radius during the first week of occupation, within a 3.2 km radius the second week, and within a 4.8 km radius the third week" (Lee, 1969).

The energy cost of obtaining mongongo nuts increases with their distance from camp. The cost curve rises gradually as the distance increases from 3 to 19 km (Figure 6.3). After 19 km, however, the cost curve rises sharply, because the gatherer must make a 2-day round trip. An overnight hike requires the gatherer to carry water and heavier loads during the entire trip.

An alternative to making longer food-gathering trips is to eat less desirable foods that can be found closer to the water holes. During the dry season, when there are fewer water holes, the bushmen use both strategies to maintain their food supplies. During these stress periods, "the older, less mobile members of camp stay close to home and collect the less desirable foods while the younger, more active members make the longer trips to the nut forests" (Lee, 1969).

During the rainy season, when there are many temporary pools of water, camps are located so that both nuts and water are relatively close. During these ideal periods, the gatherers seldom travel more than 9.7 km (6 mi) round trip to collect nuts. The total average energy expenditure for a day that includes nut collecting is about 2680 kcal. This energy expenditure can be broken down by activity, as shown in Table 6.2.

The energy expended to collect nuts gathered at an average distance of 4.8 km and the energy return from nut food can be calculated from the data of Lee (1969). Walking at 4 km/h, it takes about 1.2 h to reach the location of the nuts. Walking expends about 180 kcal/h (Table 6.1), and basal metabolism requires 45 kcal/h, for a

TABLE 6.2
Input/Output Analysis of !Kung Bushmen Gathering Mongongo Nuts at a Distance of 4.8 km from Their Camp

	h	kcal
Inputs		
Travel to location of nuts	1.2	270
Collecting nuts	3	675
Return trip to camp carrying 12.5 kg nuts	1.2	462
Subtotal		1407
Sleep	10.5	473
Other activities	8	800
Total	24	2680
Outputs		
Shelled nuts, 1.75 kg		10,500
Output/input ratio		3.9:1

Source: Based on Lee, R.B., *Environment and Cultural Behavior: Ecological Studies in Cultural Anthropology*, Natural History Press, New York, 1969.

total of 225 kcal/h. Over 1.2 h, the total energy expended is 270 kcal. Collecting nuts for an estimated 3 h at 225 kcal/h burns an estimated 675 kcal.

The return trip to camp at a distance of 4.8 km also takes about 1.2 h. However, carrying a 12.5 kg load of nuts while walking requires more calories—an estimated 385 kcal/h (340 kcal + 45 kcal basal metabolism)—than walking unencumbered does. For 1.2 h, this activity requires 462 kcal.

The bushmen rest and sleep 10.5 h/day, consuming 473 kcal (the basal rate). Postulate that other light activities are carried on for 8 h/day at 100 kcal/h (55 kcal + 45 kcal basal metabolism), or 800 kcal total. This brings the total energy expenditure per day to 2680 kcal.

The 12.5 kg load of nuts contains about 2500 nuts from which about 1.75 kg of nut meat is extracted for consumption. This volume of nut meat yields about 10,500 kcal.

With 2680 kcal expended to obtain 10,500 kcal of nuts, the basic output/input ratio is 3.9:1. Using similar assumptions but with the nuts 9.6 km distant, the output/input ratio declines only slightly, to 3.3:1 (Table 6.3).

These output/input ratios are based on data showing that women collect an average of 2.2 days/week (range 1.2 to 3.2 days) and obtain 23,100 kcal in nuts per week. This amount provides sufficient food calories for the gatherer (14,296) as well as a surplus of about 38%. The surplus is needed to help feed the children and elderly dependents who make up the third of the population that does not gather food.

If hunters and gatherers have to work an average of 2.2 days/week to obtain food, that leaves approximately 4.8 days for other activities. These include gathering

TABLE 6.3
Input/Output Analysis of !Kung Bushmen Gathering Mongongo Nuts at a Distance of 9.6 km from Their Camp

	h	kcal
Inputs		
Travel to location of nuts	2.4	540
Collecting nuts	3	675
Return trip to camp carrying 12.5 kg of nuts	2.4	924
Subtotal		2139
Sleep	10.5	473
Other activities	8	600
Total	24	3212
Outputs		
Nuts shelled, 1.75 kg		10,500
Output/input ratio		3.3:1

Source: Based on Lee, R.B., *Environment and Cultural Behavior: Ecological Studies in Cultural Anthropology*, Natural History Press, New York, 1969.

firewood, moving, constructing shelters and clothing, caring for children, and enjoying leisure time (Lee, 1969; Marshall, 1976). Observations indicate that bushmen value their leisure and enjoy dancing, visiting other camps, and engaging in other social activities.

EARLY AGRICULTURE

Although we have no written account of the evolution of agriculture, we can logically reconstruct what might have happened. No doubt early agriculture evolved slowly from less structured societies of food gatherers. We know that gatherers brought fruits, nuts, vegetables, and seeds, including grains, back to camp for consumption. As expected, some seeds were dropped on the soil in the clearing of the camp and had the opportunity to grow there. Upon returning to the same campsite some time later, the hunter-gatherers discovered a concentration of grains, vegetables, fruits, and nuts. Some of the more observant people probably associated seeds with plants and began to plant seeds themselves. The relative ease of harvesting such crops as opposed to randomly gathering food in nature would encourage more plantings. The trend toward food cultivation is thought to have been slow, with the percentage of the food supply produced from gardens gradually increasing over time.

One important step in the emergence of agriculture was the deliberate removal of existing natural vegetation, including shrubs and trees, which would interfere and compete with crop growth. Burning was the easiest and most common means of clearing the land. Thorough burning not only completely destroyed weeds but also added nutrients to the soil. Following burning, the plots were generally clear except for a few large trees and charred stumps.

Early farmers planted crops by poking holes in the soil with digging sticks and dropping the seeds into the holes. Placing seeds in the cleared ground speeded their germination and subsequent growth, so they could compete more successfully with other vegetation. After being planted, the early crops were given little or no care. A few months or even a year later, the farmers might return to harvest their crop, or what was left of it. Mammals, birds, insects, and disease organisms shared in the harvest, and weed competition reduced yields. Many of these same pest species still reduce crop yields today.

The next step in the development of agriculture was to expand the crop plantings sufficiently to produce most of the food supply. With time, the camps became relatively permanent because an ample food supply existed nearby; men and women no longer had to travel to find food. Living close to the plantings allowed a group to claim ownership and to protect the plantings from other humans as well as from mammals, birds, and other pests.

Early plots were planted and harvested for about 2 years, then abandoned because production declined as nutrients in the soil became depleted and other problems (such as pest outbreaks) developed. Interestingly, this "cut/burn," or "swidden," type of agriculture is still practiced today in many parts of the world (Ruthenberg, 1971). Swidden agriculture requires that farmed land lie fallow for 10 to 20 years before it can be cleared again and farmed. During the long fallow period, the soil gradually accumulates the nutrients needed for successful crop production.

Swidden agriculture can cause severe soil erosion problems, especially when practiced on slopes in large hectarages. Erosion, of course, is a major global problem with all crop production systems, but the damage is intensified when hilly cropland is left without vegetation. Also, if crop residues are harvested and burned, the soil is left unprotected and susceptible to erosion. Thus, there is reason to discourage the burning of crop residues.

A study of a primitive agricultural society in New Guinea provides many insights into the energy inputs and outputs of a Swidden-type agricultural system (Rappaport, 1968, 1971). New Guinea has a tropical mountainous ecosystem with about 3910 mm of rainfall per year. The relatively steep slopes and heavy rainfall combine to make soil erosion a problem. These primitive agriculturalists, however, practice soil conservation by employing several of the conservation techniques previously mentioned.

When the New Guinea community was studied, the village numbered 204 inhabitants and occupied about 830 ha. Only about 364 ha of this land was suitable for cultivation. The village annually planted about 19 ha of crops, but because some crops required 2 years before they could be harvested, about 37 ha were cultivated at any one time. As a result, nearly 90% of the village croplands lay fallow each year.

The villagers' food was almost entirely (99%) of plant origin. The primary plants consumed (by weight) were taro, sweet potato, fruit, leaves, yams, and bananas (Figure 6.4). The animal protein came primarily from pigs raised by the villagers, who also hunted and ate marsupials, snakes, lizards, birds, and insect grubs.

The adult person's diet averaged about 2400 kcal/day and contained about 35 g of protein, mostly of plant origin (Rappaport, 1968). This protein intake is low by current Food and Agriculture Organization (FAO) standards, which recommend a daily intake of about 40 g of protein per day for an adult living under these conditions.

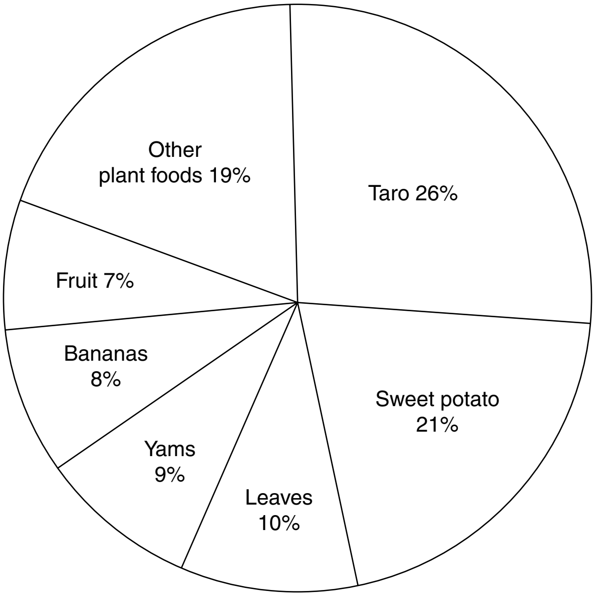

FIGURE 6.4 Percentage of the plant materials consumed by the villagers in New Guinea.

As expected, food production in swidden agriculture is labor intensive. The New Guinea villagers worked an estimated 1869 h/ha/year in crop production (Rappaport, 1968, 1971). About 42% of the labor input went into weeding, 15% into clearing trees and brush (Table 6.4). Another substantial labor input was for transporting the harvest from the garden plots to people's homes. This activity required about 277 h but was often viewed as a pleasure because the villagers took pride in harvesting their crops.

The total energy input to raise 1 ha of crops under the New Guinea agricultural system was about 739,160 kcal (Table 6.4). The crop yield averaged about 11.4 million kcal/ha, resulting in an output/input ratio of 15.4:1 (Rappaport, 1968, 1971).

If we assume an average daily per capita consumption of 2400 kcal, an individual would consume about 876,000 kcal/year. Hence, a 1-ha plot would provide sufficient food energy for 13 persons, and the 37 ha usually cultivated by the villagers would provide more than enough food for the inhabitants. However, the villagers consumed only 55% of the energy value of their crops and fed about 45% to their pigs. When this is taken into account, the ratio of people to land decreases; only 5.5 persons are sustained per hectare planted.

Rappaport (1971) reported that each pig required a total of 4.5 million kcal of feed over a 10-year period. If we assume that about 65 kcal of feed are required to produce 1 kcal of pork (Pimentel et al., 1975), the return from 4.5 million kcal of feed would be 69,230 kcal of pork. This represents only a 1.5% return on the food energy fed to the pigs.

From the 11.4 million kcal/ha harvested, as noted, 45% (5.1 million kcal/ha) was fed to the pigs. If 65 kcal were required to produce 1 kcal of pork, the yield would

TABLE 6.4
Output/Input Analysis of New Guinea Swidden Agriculture for 1 ha of Mixed Crops That Included Sweet Potato, Taro, Cassava, Yam, and Banana

	h/ha	kcal/h	kcal/ha
Inputs			
Clearing underbrush	175	400	70,000
Clearing trees	68	400	27,200
Fencing garden	84	500	42,000
Weeding and burning	78	300	23,400
Placing soil retainers	44	400	17,600
Planting and all weeding	742	300	222,600
Other maintenance	137	400	54,800
Harvesting	277	300	83,100
Cartage	264	400	145,600
Subtotal	1869		686,300
Axe, machete (0.8 kg)[a]			16,860
Seeds, etc. (10 kg)[a]			36,000
Total			739,160
Outputs			
Crop yield			11,384,462
Output/input ratio			15.4:1

[a] Estimated as additional inputs.

Source: After Rappaport, R.A., *Pigs for the Ancestors: Ritual in the Ecology of a New Guinea People*, Yale University Press, New Haven, 1968 and *Scientific American* 225, 116–132, 1971.

be only 78,461 kcal/ha. This 78,461 kcal, added to the 6.3 million kcal consumed directly by humans, provides a total yield of food energy of 6.4 million kcal/ha.

Rappaport (1968, 1971) mentions one advantage to pork production: Keeping pigs was a practical way to store some of the excess food during productive years. When crop harvests were poor, the villagers slaughtered some of the pigs to provide the needed food.

Another study of Swidden-type agriculture was conducted in a village in the Tepoztlan region of Mexico (Lewis, 1951). The manpower input for raising the staple food—corn—was 1144 h/ha, compared with 1869 h in New Guinea (Table 6.5).

Calculations for total energy output/input for this system are listed in Table 6.5. Basic activities directly related to corn production involved an expenditure of 344,800 kcal, with 64,350 kcal expended during rest and 85,800 kcal spent for miscellaneous activities. When the energy costs of the axe, hoe, and seeds are added, the total energy input to raise 1 ha of corn was 548,410 kcal. With a crop yield of 6.8 million kcal, the resulting output/input ratio was 12.6:1. This output/input ratio was only slightly lower than the New Guinea swidden agricultural system, which had a ratio of 15.4:1.

TABLE 6.5
Energy Inputs in Corn Production in Mexico Using Swidden Agriculture

	h/ha	kcal/h	kcal/ha
Inputs			
Clearing with machete and axe	320	400	128,000
Fencing with poles	96	400	38,400
Burning	64	300	19,200
Seeding	96	300	38,400
Reseeding	32	300	9600
Weeding	240	300	72,000
Transporting corn	80	400	3200
Shelling corn	120	300	36,000
Subtotal	1144		344,800
Rest	1430		64,350
Other activities	858		85,800
Axe and hoe (0.8 kg)[a]			16,860
Seeds, etc. (10.4 kg)[a]			36,600
Total			548,410
Outputs			
Crop yield	1944 kg		6,901,200
Output/input ratio			12.6:1

[a] Estimated as additional inputs.

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

Thus, even primitive societies vary in the energy efficiencies of their methods of securing or producing food. The early hunter-gatherers were probably much like the !Kung bushmen of today, who have an average output/input ratio of about 4:1 under ideal conditions. Somewhat more organized agricultural production systems like those of the villagers in New Guinea and Mexico have more favorable energy ratios of 12 to 15:1. In addition, less land per person is necessary in those systems where increased crop culture is practiced.

REFERENCES

Clark, C. and M. Haswell. 1970. *The Economics of Subsistence Agriculture*. London: MacMillan.

Lee, R.B. 1969. !Kung Bushman subsistence an input-output analysis. In A.P. Vayda (ed.), *Environment and Cultural Behavior: Ecological Studies in Cultural Anthropology*, pp. 47–79. Garden City, NY: Natural History Press.

Lee, R.B. and I. DeVore. 1976. *Kalahari Hunter-Gathers*. Cambridge, MA: Harvard University Press.

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

Marshall, L.J. 1976. *The !Kung of Nyae Nyae*. Cambridge, MA: Harvard University Press.

Pimentel, D., W. Dritchillo, J. Krummel, et al. 1975. Energy and land constraints in food-protein production. *Science* 190: 754–761.

Pyke, M. 1970. *Man and Food*. New York: McGraw-Hill.

Rappaport, R.A. 1968. *Pigs for the Ancestors: Ritual in the Ecology of a New Guinea People*. New Haven: Yale University Press.

Rappaport, R.A. 1971. The flow of energy in an agricultural society. *Scientific American* 225: 116–132.

Ruthenberg, H. 1971. *Farming Systems in the Tropics*. Oxford: Clarendon Press.

Sahlins, M. 1972. *Stone Age Economics*. Chicago, IL: Aldine-Atherton.

Whittaker, R.H. and G.E. Likens. 1975. The biosphere and man. In H. Lieth and R.H. Whittaker (eds.), *Primary Productivity of the Biosphere*, pp. 305–328. New York: Springer-Verlag.

7 Early Livestock Systems and Animal Power

Throughout history, humans have depended upon animals for food, power, and companionship. Humans have worshipped animals such as the tiger, leopard, and lion. Even today, animals seem to symbolize a special power; one can purchase a Jaguar, Eagle, or Ram automobile. The major role of animals, however, has been to provide food and to supply power to help humans cultivate their crops, build their shelters, and transport their supplies.

All available evidence tends to confirm that humans are omnivores. Humans have the capacity to consume not only a wide variety of plant materials but also animal flesh and milk. The relative proportion of plant to animal food consumed varies with cultural habits, availability of food, and personal preference.

EARLY ANIMAL HERDING

Early civilizations depended upon both animal husbandry and crop culture to supplement hunting and the gathering of wild foods. The first animals kept by humans as a source of food were chickens, ducks, pigs, rabbits, sheep, goats, cattle, camels, donkeys, and llamas. These animals provided meat, fat, milk, and blood for energy and protein and supplied other major nutrients.

Animal husbandry probably began when a hunter carried his prey's young back to camp. There, fed and protected, the animals thrived and could be killed when humans needed additional food. Later on, some of the captive animals were tamed and allowed to reproduce. Eventually, the numbers in captivity were sufficient not only to provide immediate food but also to breed, thus ensuring a continuing, stable food supply.

Herding was more efficient and dependable than hunting because it greatly reduced the time and energy humans spent in pursuit of animal foods. Further, the work involved in herding was easily done by weaker members of the group, thus freeing more able individuals to do other tasks necessary to the survival of the community.

In addition, maintaining herds of sheep, goats, cattle, and camels was a dependable way to store surplus food produced during highly successful crop years. Rather than wasting the surplus, the people could feed it to their animals. In periods of poor environmental conditions, when crop yields were low, the livestock were an available food supply.

The stabilization of the food supply through animal husbandry was even more helpful to those humans who lived in marginal habitats. In severely wet, dry, cold, or mountainous environments, crop production is difficult, unpredictable, and sometimes nearly impossible. Moreover, the tolerant grasses and other types of forage that grow well in many of these habitats are not suitable food for humans. However, these plants are suitable food for livestock, which convert them into meat, milk, and blood that humans can utilize.

The herding carried out by the Dodo tribe of northeast Uganda illustrates the advantages of husbanding livestock in marginal habitats (Deshler, 1965). During the Deshler study, the Dodo tribe numbered about 20,000 and herded about 75,000 head of Zebu cattle over an area of about 780,000 ha, or approximately 10 ha per head of cattle. The human population density was low, about 1 per 39 ha, making the ratio of cattle to people about 3.75:1. Based on a biomass comparison, the cattle outweighed the human population by more than 18 to 1.

The habitat in which the Dodos live is bleak, consisting primarily of thorn scrub and perennial grasses and having an average rainfall of between 450 and 620 mm per year. In addition to herding, the Dodos cultivate sorghum, which has ample yields during good rainfall years. However, low rainfall years also are common in that part of Uganda, making sorghum an unreliable food resource. When the sorghum harvest is poor, the cattle provide the needed food in the form of milk, blood, and meat. In addition, cattle are traded for money, which is used to purchase sorghum when local supplies are inadequate.

The 75,000 cattle yield an estimated 2.5 billion kcal in milk, 2.3 billion kcal in meat, and 630 million kcal in blood annually (Pimentel et al., 1975; Westoby et al., 1979). To produce this total of 5.43 billion kcal of food energy, the Dodos feed the cattle no grain, only pasture forage that is unsuitable for human consumption. Forage consumption is estimated at 8 kg per animal per day (Pimentel et al., 1975; Westoby et al., 1979).

The Dodos use little or no fossil fuel in managing this livestock, and work is done by human power. With the Dodo population estimated at 20,000, and assuming that 40% of the males work 56 h/week and 40% of the females work 7 h/week in herding (totaling 26.2 million hours), the estimate is that 34 human hours per hectare of grazing land per year are invested in managing this livestock population. The annual yield in animal protein is 0.7 kg/ha annually.

The energy input is calculated to be 250 kcal per working hour. Assuming that male herders work 8 h per day with an expenditure of 250 kcal/h, rest 10 h at 45 kcal/h, and spend 6 h at other activities at 100 kcal/h, the daily energy input per herder is 3050 kcal. With an estimated 8000 male herders caring for the cattle, this totals 24.4 million kcal/day, or 8.9 billion kcal/year. The females average only 1 h of herding work per day, spending most of their time caring for the sorghum plots (Deshler, 1965). When the annual female input in herding (730 million kcal) is added to the male input, the total comes to 9.6 billion kcal per year.

With 5.4 billion kcal of animal protein produced and an energy input of 9.6 billion kcal, the output/input ratio is only 0.54:1, or about 2 cal of input per 1 calorie output. Based on the animal protein produced, the Dodo could not maintain themselves only on livestock. However, as mentioned, sorghum is a staple food of the Dodo. Thus, livestock protein is used to supplement the sorghum raised or purchased.

The Dodo tribe illustrates the important role livestock can play in providing food for humans. First, the livestock effectively convert forage growing in the marginal habitat into food suitable for humans. Second, the herds serve as stored food resources. Third, the cattle can be traded for sorghum grain during years of inadequate rainfall and poor crop yields.

ANIMAL POWER AS AN ENERGY SOURCE

For most of the time that humans have inhabited the Earth, their prime source of power has been their own muscle power. They moved about on foot, carried their own goods, tilled their own land, planted, cultivated, and harvested crops through their own labor, ground cereals by hand, hunted animals with arrows and spears, and protected themselves from animal predators and human attackers.

Early additional sources of power included human slaves and domesticated animals. The hunting/gathering societies were helped when an extra food gatherer or hunter could join in the task of securing food. Likewise, the labor intensiveness of primitive agriculture increased both the need for and the usefulness of slave and animal labor.

In hunting, one or two persons could guide wild game to a concealed hunter, and an additional hunter could help in the exhausting task of tracking and killing the wounded prey. Usually the killing of large animals required the efforts of several hunters. Even after the kill, considerable energy was expended in transporting the carcass back to camp, often a long distance away. Thus, additional manpower was a distinct asset both during a hunt and after a successful kill.

The slave or extra hunter, of course, would have to be fed. However, two hunters could kill more than twice as much game as a single hunter could kill alone. In this way, additional labor provided a greater return in energy than the energy input required for its maintenance.

Along with slaves, animals slowly emerged as an additional source of power for humans. Young animals captured in the wild could be tamed and later used to transport goods and people. At first these animals were probably used to carry collected food or animal carcasses back to camp. In addition, nomadic groups used animals to move their belongings to new campsites.

Over time, many kinds of animals have served as beasts of burden. The earliest records of such use show that donkeys served humans in Egypt about 3000 B.C. (Leonard, 1973) and later in Mesopotamia about 1800 B.C. (Zeuner, 1963). Agriculture was already an important activity of these societies, and animals were used to transport the harvest from the field to the village. Gradually, aided by this improved mode of transportation, trade between villages developed.

As early as 2500 B.C., cattle, including oxen and water buffalo, were used to transport people and goods and to draw plows (Leonard, 1973). The use of animal power to cultivate the soil was an immense breakthrough in agricultural production. Tremendous quantities of energy and about 400 h of heavy labor were expended when humans worked alone to turn 1 ha of soil for planting. With 1 h of ox power substituting for 3–5 h of human power, the time and energy requirement was drastically reduced.

The use of horses followed and was a significant improvement over oxen because horses move faster. Best estimates are that horses first inhabited Asia but were probably not domesticated until 3000 B.C. (Lee, 1955). As with oxen, horses were first used to transport goods and people and later to help humans till their fields. Other animals that have been used to carry humans and their goods include camels, llamas, goats, and even dogs.

About 3000 B.C., the invention of the wheel made possible a tremendous increase in the efficiency of transportation (Lee, 1955). The wheel doubled the load of goods that could be transported per unit of energy. The surplus energy was then available for use in other ways and undoubtedly helped humans improve their standard of living.

In addition, the wheel led to improved efficiency in other food-related processes, such as grinding cereals. Grinding grain by hand was slow and tedious. Animals powered the early grinding wheels, but later humans found ways to harness wind and water for power. Of course, wind and water power were significantly more efficient than animal power because they did not require food for maintenance.

Although wind and water power are more efficient than either animal or human power for grinding grain, there are many tasks for which human power is the most efficient energy source. This can be illustrated by analyzing the energy inputs in tilling soil and applying herbicides. A person using a heavy hoe to till 1 ha of soil for planting needs about 400 h, or 40 work days of 10 h each, to complete the task (Lewis, 1951). If we assume that the individual expends 400 kcal/h for this heavy work, this amounts to 4000 kcal expended per 10-h day (though it is doubtful that a person could maintain a 400 kcal/h pace for 10 h). Additional energy is required to maintain the worker for the other 14 h each day. If we assume the worker rests for 10 h at 45 kcal/h and spends the other 4 h involved in miscellaneous light activities requiring an average of 100 kcal/h, the total energy expenditure for one person tilling the soil is 4850 kcal/day. When this daily energy expenditure is multiplied by 40 days of work, the total energy input is about 194,000 kcal (Table 7.1). An added

TABLE 7.1

Comparison of Energy Inputs for Tilling 1 ha of Soil by Human Power, Oxen, 6-HP Tractor, and 50-HP Tractor

Tilling Unit	Required Hours	Machinery Input (kcal)	Petroleum Input (kcal)	Human Power Input (kcal)	Oxen Power Input (kcal)	Total Input (kcal)
Human power	400	6000	0	194,000	—	200,000
Oxen (pair)	65	6000	0	31,525	260,000[a]	297,525
6-HP tractor	25	191,631	237,562[b]	12,125	—	441,318
50-HP tractor	4	245,288	306,303[c]	1940	—	553,531

[a] Each ox is assumed to consume 20,000 kcal of feed per day.

[b] An estimated 23.5 L of gasoline used.

[c] An estimated 30.3 L of gasoline used.

Source: Pimentel, D. and Pimentel, M., *Food, Energy and Society*, Edward Arnold, London, 1979.

6000 kcal input is required for the construction and maintenance of the heavy hoe. Thus, the total energy input to till 1 ha by human labor alone is about 200,000 kcal.

Oxen, small hand tractors, and 50-HP tractors all require a greater total energy expenditure to till the same hectare of land. However, it should be noted that all these other power systems can complete the tilling task in far less time than a human can. For example, two oxen take only 65 h but expend almost 50% more energy than a human tiller does (Table 7.1). The oxen must be fed and need a person to guide them as they work. Likewise, 6-HP and 50-HP tractors take much less time—25 and 4 h, respectively—to till 1 ha than humans. But they use far more energy than either humans or oxen because of the large input of petroleum needed to run the engines.

Considering the current prices of fuel, hay, and labor in all countries, it is generally more economical to till the soil with either machinery or oxen than with human labor alone. If prices of fuels rise, machinery may no longer be quite the energy bargain it is today.

Tilling the soil is an extremely heavy task for both humans and tractors. To keep the relative efficiencies of human labor and tractors in perspective, it is helpful to compare energy inputs involved in applying herbicides. A person takes about 3 h to hand-spray 1 ha with herbicide, expending an estimated 300 kcal/h, plus nonworking inputs, for a total of 1455 kcal. Adding 8 kcal for the construction and maintenance of the hand-sprayer brings the total input for the spraying task to 1463 kcal (Table 7.2).

The 50-HP tractor using a power-driven sprayer requires only 0.7 h to spray 1 ha. The gasoline input is estimated at 3 L, or 30,327 kcal of energy, and the human labor input for 0.7 h is assumed to be 340 kcal. An added 21,463 kcal of energy is expended for the construction and maintenance of both tractor and sprayer. Thus, the total energy input for tractor-spraying is about 52,130 kcal, or about 37 times more than for hand-spraying (Table 7.2). Obviously, using a 50-HP tractor for this task is energy intensive; in fact, the tractor is too highly powered for such light work. The tractor and sprayer weigh 5–6 tons, and a large input of energy is needed to move these weights over the field.

When only the dollar cost is considered, applying herbicide manually would be more economical than employing a tractor. Thus, in a country where farm

TABLE 7.2

Comparison of Energy Inputs for Spraying Herbicide on 1 ha by Human Power and 50-HP Tractor

Spraying Unit	Required Hours	Machinery Input (kcal)	Petroleum Input (kcal)	Human Power Input (kcal)	Total Input (kcal)
Human power	3.0	8	0	1455	1463
50-HP tractor	0.7	21,463	30,327[a]	340	52,130

[a] An estimated 3 L of gasoline used.

Source: Pimentel, D. and Pimentel, M., *Food, Energy and Society*, Edward Arnold, London, 1979.

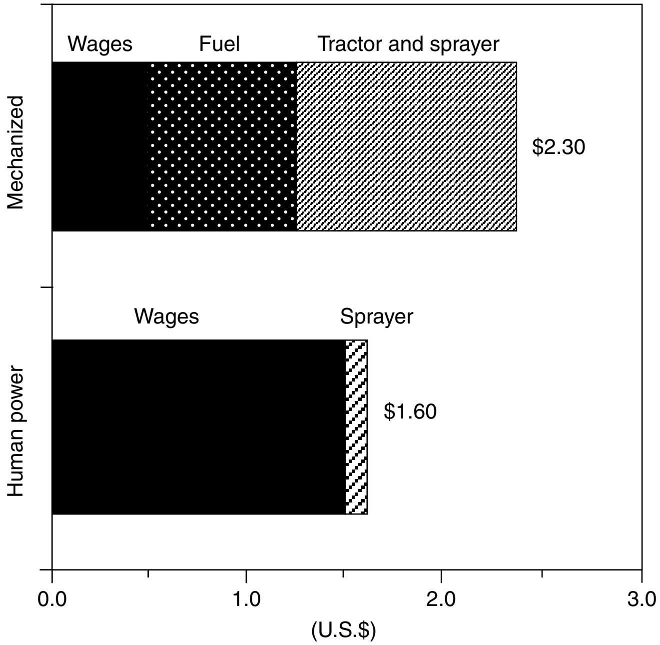

FIGURE 7.1 Economic costs of applying herbicide in a developing country.

wages might be as low as $0.50 per hour, applying herbicide manually would cost an estimated $1.60, whereas using a tractor would cost an estimated $2.30 (Figure 7.1). Hand-spraying becomes increasingly expensive as the hourly wage for labor increases.

In these comparisons, nothing has been said about the type of energy used, and this is a vital factor to consider. Humans need food, the tractor depends on petroleum, and the ox consumes forage, a plant product that humans cannot use for food. In many regions, forage is a free energy source. Forage growing along paths, waterways, and similar areas that do not compete with croplands can be fed to the oxen or other draft animals. Also, straw left after the harvest of rice or similar grain crops can be fed to animals. Hence, the energy cost of maintaining an ox might be minimal to the small farmer. Draft animals have additional advantages because they provide milk and meat as well as power. With animal protein foods at a premium in some developing countries, this supply of milk and meat has great nutritional value.

Many nations have replaced draft animals with tractors and other machinery. For example, when the United States was first settled in 1620, human power was the prime power source for work, but by 1776 an estimated 70% of the power was supplied by animals and only 20% by humans (Cook, 1976). By 1850 animal power had declined to 53% and manpower to 13% (Cook, 1976) (Figure 7.2). By 1950, about 100 years later, animal and human power had declined to only about 1%, and fossil-fuel-powered engines provided 95% of the power. Thus, a dramatic change with far-reaching consequences has taken place, as humans continue to consume ever-increasing quantities of nonrenewable fossil fuels.

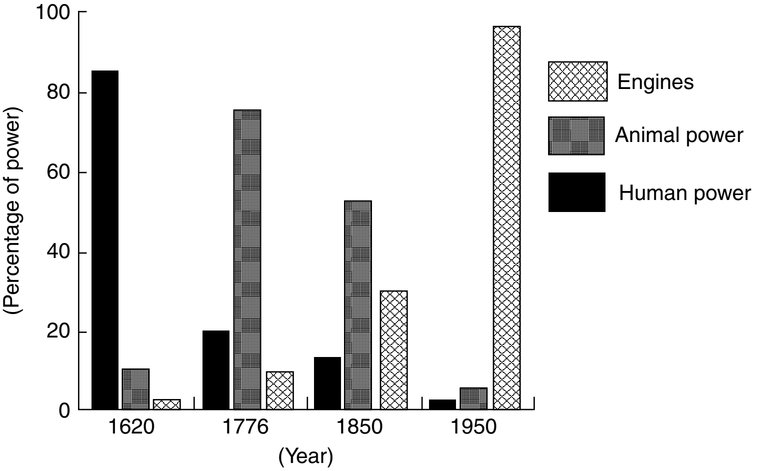

FIGURE 7.2 The percentage of power provided by human power, animal power, and engines during various periods in U.S. history. (*Sources*: 1620, estimated; 1776, 1850, and 1950, from Cook, E., *Man, Energy, Society*, W.H. Freeman, San Francisco, 1976.)

ANIMAL FOOD-CONSUMPTION PATTERNS

Throughout history animals, either hunted or husbanded, have been valued by humans for food. Even so, the majority of humankind has had to depend primarily on plant materials for energy and other nutrients. Even today most of the world's people live on about 2500 kcal per day and obtain most of their food energy and protein from grains and legumes (Worldwatch Institute, 1992).

Historical examples are numerous. One of the unique human diets on record was consumed in Ireland during the nineteenth century. At this time the Irish people relied primarily on potatoes for both calories and protein, consuming about 4.5 kg of potatoes and half a liter of milk each day (Connell, 1950). These two foods provided about 3852 kcal and 64 g of protein per day, of which 45 g were from the potatoes.

Or recall the diet of the New Guinea villagers studied by Rappaport (1968), who consumed primarily plant foods (Figure 6.4). About 99% of their calories came from plant material. A study of 12 rural villages in southern India showed that individuals consumed, on average, between 210 and 330 g of rice and wheat, 140 ml of milk, and 40 g of pulses and beans per day (Tandon et al., 1972). This diet provided about 1500 kcal and 48 g of protein per day, with the major share of both calories and protein coming from plants.

In Central America, laborers commonly consume about 500 g of corn per day (E. Villager, ICAIITI, personal communication, 1975). Along with the corn they eat about 100 g of black beans per day, and together these staples provide about 2118 kcal and 68 g of protein daily. The corn and beans complement each other in providing the essential amino acids that humans need. Additional food energy is obtained from other plant and animal products.

A sharp contrast to all these examples is found in the United States, where the daily protein intake is 112 g, of which 75 g is animal protein. U.S. per capita animal

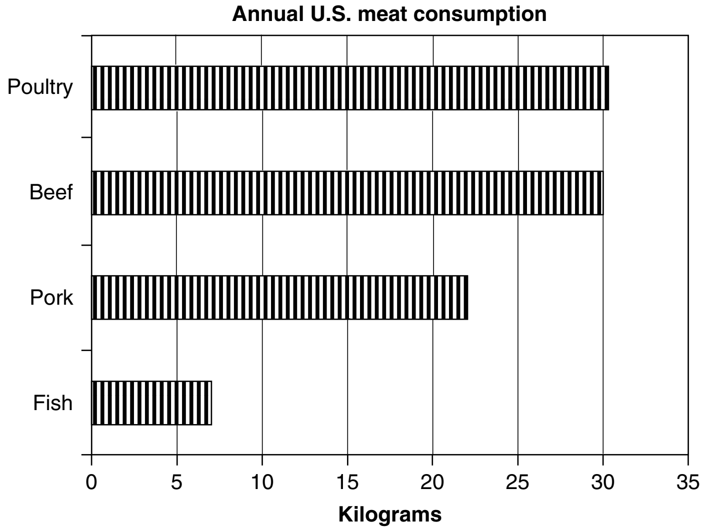

FIGURE 7.3 Annual meat consumption per person in the United States. (From USDA, *Agricultural Statistics 2006*, Government Printing Office, Washington, D.C., 2003.)

and animal protein consumption is among the highest in the world, although similar consumption patterns appear in many highly industrialized nations in Europe (FAO, 1991). In 2006, annual U.S. per capita meat consumption was 92 kg. Poultry is the meat eaten in the largest quantity (Figure 7.3). In addition, annual per capita food consumption includes 14 kg of eggs and about 260 kg of milk and dairy products.

Although mammals and mammal products, such as milk and cheese, dominate the animal products consumed by humans, a great variety of other animal material is also eaten, including many kinds of birds and their eggs, ranging all the way from large ostrich eggs to tiny birds such as the English sparrow. Often the small birds, plucked of feathers and cooked on skewers, are eaten whole, bones and all (Laycock, 1986). Eggs are eaten in a variety of ways: raw, cooked, incubated, preserved, and pickled. Some uniquely prepared eggs are the Chinese, or "century" eggs and the Philippine *balut*. Century eggs are preserved in lime, coated with clay, and buried for long periods of time. As the name implies, century eggs will keep for many years. After the preservation, the white portion of the egg has become black and gelatinous, the yolk a dark green to black color. Balut, a Philippine delicacy, is a duck egg that has been fertilized and incubated for about 17 days. On day 21 a young duckling normally would hatch from the egg, so at day 17 a fairly well-developed young duckling is present within the shell. The egg is boiled and eaten hot or cold.

Fresh and saltwater fishes and their eggs are also favorite foods when supplies are easily accessible and ample. Fish are prepared in many different ways—raw, salted, smoked, dried, boiled, baked, broiled, and by combinations of these processes.

People in many parts of the world eat arthropods, such as shrimp, crayfish, lobster, and their close relatives, the insects. In Europe and the United States, shrimp, crayfish, and lobster are some of the most highly valued and highly priced foods, yet their small insect relatives are considered unacceptable. In fact, the U.S. government has established various regulations to ensure that insects and insect parts are kept to a minimum in food. The small herbivorous insects present in U.S. foods despite the regulations include aphids, thrips, and dipterans. Some large insects that are intentionally used as food include grubs, locusts, and grasshoppers (Pimentel et al., 1993).

Lizards, snakes, snails, and frogs are also eaten by many people. In fact, some cultures consider frogs and snails a delicacy. Lizards and snakes are also eaten and are reported to be excellent food.

NUTRITIONAL QUALITY OF PROTEIN FOODS

One of the important considerations in evaluating the relative value of plant and animal protein sources is their nutritional content. A broad comparison shows, for instance, that one cup of cooked dried beans (190 g) is quite similar to an 85 g serving of cooked ground beef in the amounts of protein, iron, and important B vitamins. Further, the beans contain no fat, no cholesterol, and no vitamin B_{12}.

Although these foods contain similar amounts of protein, the nutritional quality of the protein differs in terms of both the kind and amounts of "nutritionally essential" amino acids. Animal proteins contain the eight essential amino acids in optimum amounts and in forms utilizable by humans for protein synthesis. For this reason, animal proteins are considered high-quality proteins.

By comparison, plant proteins contain lesser amounts of some of the essential amino acids and are judged to be lower in nutritional quality than animal sources. In addition, some plant proteins are deficient in one or more essential amino acids. For example, cereal grains as a group are relatively low in lysine, whereas legumes, such as dried beans and peas, are relatively low in methionine but have ample amounts of lysine. Fortunately, it is possible to combine plant proteins to complement the amino acid deficiencies. Thus, when cereal and legume proteins are eaten together, the combined amino acid supply is of better quality than that provided by either food eaten alone.

More attention and thought must be given to planning a diet that is either limited in or entirely devoid of animal protein. Variety is of prime importance in achieving a nutritionally balanced diet under such constraints. Further, because B_{12}, an essential vitamin, is not found in plant foods, this must be taken as a supplement. The diets of nutritionally vulnerable individuals, such as infants, growing children, and pregnant women, often require additional supplements when a strict plant food regime is undertaken. Individuals in these categories often find it difficult to consume the quantity of plant material necessary to provide such essential nutrients as calcium and iron.

Another advantage of animal products over plant products as food for humans, especially children, is the greater concentration of food energy per unit of weight compared with plant material. For example, to obtain 375 kcal of food energy from sweet corn one has to consume 455 g, whereas one can derive the same amount of food energy (375 kcal) from only 140 g of beef. Thus, beef has more than three times as much food energy per unit of weight as sweet corn.

REFERENCES

Connell, K.H. 1950. *The Population of Ireland*. Oxford: Clarendon Press.

Cook, E. 1976. *Man, Energy, Society*. San Francisco, CA: W.H. Freeman.

Deshler, W.W. 1965. Native cattle keeping in Eastern Africa. In A. Leeds and A.P. Vayda (eds.), *Man, Culture and Animals*. Washington, D.C.: AAAS Publication No. 78.

Food and Agriculture Organization (FAO). 1991. *The State of Food and Agriculture*. Rome: Food and Agriculture Organization of the United Nations.

Laycock, G. 1986. *The Alien Animals*. New York: Natural History Press.

Lee, N.E. 1955. *Travel and Transport Through the Ages*. Cambridge, UK: Cambridge University Press.

Leonard, J.N. 1973. *The First Farmers*. The Emergence of Man Series. New York: Time-Life Books.

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

Pimentel, D. and M. Pimentel. 1979. *Food, Energy and Society*. London: Edward Arnold.

Pimentel, D., W. Dritchillo, J. Krummel, et al. 1975. Energy and land constraints in food-protein production. *Science* 190: 754–761.

Pimentel, D., C. Kirby, and A. Shroff. 1993. The relationship between "cosmetic" standards for foods and pesticide use. In D. Pimentel and H. Lehman (eds.), *The Pesticide Question: Environment, Economics, and Ethics*, pp. 85–105. New York: Chapman & Hall.

Rappaport, R.A. 1968. *Pigs for the Ancestors: Ritual in the Ecology of a New Guinea People*. New Haven, HT: Yale University Press.

Tandon, B.N., K. Ramachandran, M.P. Sharma, et al. 1972. Nutritional survey in rural population in Kumaon Hill area, North India. *American Journal of Clinical Nutrition* 25: 432–436.

U.S. Department of Agriculture (USDA). 2006. *Agricultural Statistics 2006*. Washington, D.C.: Government Printing Office.

Westoby, M., J. Krummel, W. Dritschillo, et al. 1979. Direct and indirect use of land, labor, and fossil fuels by some animal production systems. *Environmental Biology Report 79–1*. Ithaca, NY: Cornell University.

Worldwatch Institute. 1992. *State of the World 1992*. Washington, D.C.: Worldwatch Institute.

Zeuner, F.E. 1963. *A History of Domesticated Animals*. New York: Harper & Row.

8 Livestock Production and Energy Use

Worldwide an estimated 2 billion people live primarily on a meat-based diet while an estimated 4 billion people live primarily on a plant-based diet (Pimentel et al., 1999). The shortage of cropland, freshwater, and energy resources requires that most of the 4 billion people live primarily on a plant-based diet; however, there are serious food shortages worldwide. For instance, the World Health Organization recently reported that more than 3 billion people are malnourished in the world (WHO, 2000). This is the largest number and proportion of malnourished people ever recorded in history. In large measure, the food shortage and malnourishment problem are primarily related to rapid population growth in the world in addition to the declining per capita availability of land, water, and energy resources required for food production (Pimentel and Pimentel, 2003).

Meat, milk, and eggs contribute valuable nutrients to the human diet in the United States and the world. To produce animal protein successfully requires the expenditure of human and fossil energy to supply livestock forage and grain. The land, devoted to grain or forage for livestock production, is exposed to soil erosion which slowly diminishes the fertility of the soil and its productivity (Pimentel, 2006). Additionally, animal production requires large inputs of water for grain and forage crops and, to a lesser extent, directly for animal consumption. All of these factors interact to determine the ultimate success of animal production systems (Pimentel, 1997).

In this chapter, I include an analysis of the quantities of animal products produced; energy, land, and water resource inputs in livestock production; and meat, milk, and egg production.

ANIMAL PRODUCTS CONSUMED IN THE U.S. DIET

In the United States, more than 8 billion livestock are maintained to supply the animal protein consumed annually (USDA, 2001). In addition to the large amount of cultivated forage, the livestock population consumes about seven times as much grain as is consumed directly by the entire American population (Pimentel and Pimentel, 2003).

From the livestock population of more than 8 billion, approximately 7.5 million tons (metric) of animal protein is produced each year (Table 8.1). If distributed equally, it would be sufficient to supply about 75 g of animal protein daily per American. With the addition of 37 g of available plant protein, a total of 112 g of

TABLE 8.1
Number of Livestock in the United States

Livestock and Livestock Products	Number × 10^6
Sheep	7
Dairy	13
Swine	60
Beef cattle	74
Turkeys	273
Broilers	8000
Eggs	77,000

Source: USDA, *Agricultural Statistics*, U.S. Department of Agriculture, Washington, D.C., 2001.

protein is available per capita (Pimentel and Pimentel, 2003). In contrast, the RDA (recommended daily allowance) per adult per day is 56 g of protein for a mixed diet for an adult. Therefore, based on these data, each American is consuming about twice the RDA for protein per day.

About 144 kg of meat, including fish, is eaten per American per year (Pimentel and Pimentel, 2003). In addition, 271 kg of milk and eggs are consumed per capita in the United States per year.

ENERGY INPUTS IN ANIMAL PRODUCT PRODUCTION

Each year an estimated 45 million tons of plant protein are fed to U.S. livestock to produce approximately 7.5 million tons of animal protein for human consumption (USDA, 2001). To produce this animal protein, about 28 million tons of plant protein from grain and 17 million tons of plant protein from forage are fed to the animals (Table 8.2). Thus, for every kilogram of high quality animal protein, livestock are fed nearly 6 kg of plant protein. In the conversion of plant protein into animal protein, there are two principal "costs": (1) the direct costs of production of the harvested animal including the grain and forage and (2) the indirect costs for maintaining the breeding animals (mother and father).

The major fossil energy inputs for grain and forage production include fertilizers, farm machinery, fuel, irrigation, and pesticides (Pimentel et al., 2002). The energy inputs vary according to the particular crop and forage being grown. When these inputs are balanced against their energy and protein content, grains and some legumes like soybeans are produced more efficiently in terms of energy inputs than are fruits, vegetables, and animal products (Pimentel and Pimentel, 1996; Pimentel et al., 2002). In the United States, the average protein yield of the five major grains (plus soybeans) fed to livestock is about 700 kg/ha. To produce a kilogram of plant protein requires about 10 kcal of fossil energy (Pimentel et al., 2002).

Forage can be fed to ruminant animals, such as cattle and sheep, because they can convert forage cellulose into usable nutrients through microbial fermentation.

TABLE 8.2
Grain and Forage Inputs per Kilogram of Animal Product Produced, and Fossil Energy Inputs (kcal) Required to Produce 1 kcal of Animal Protein

Livestock and Livestock Products	Grain (kg)[a]	Forage (kg)[b,c]	kcal Input/kcal Protein
Lamb	21	30	57:1
Beef cattle	13	30	40:1
Eggs	11	—	39:1
Beef cattle	—	200	20:1
Swine	5.9	—	14:1
Dairy (milk)	0.7	1	14:1
Turkeys	3.8	—	10:1
Broilers	2.3	—	4:1

[a] From USDA, *Agricultural Statistics*, U.S. Department of Agriculture, Washington, D.C., 2001.

[b] From Heischmidt, R.K., Short, R.E., and Grings, E.E., *Journal of Animal Science* 74(6), 1395–1405, 1996.

[c] From Morrison, F.B., *Feeds and Feeding*, Ithaca, NY: The Morrison Publishing Company, 1956.

The total plant protein produced on good U.S. pasture and fed to ruminants is 60% of the amount produced by grains (Table 8.2). Current yield of beef protein from productive pastures is about 66 kg/ha, while the energy input per kilogram of animal protein produced is 3500 kcal (Pimentel and Pimentel, 1996). Therefore, animal protein production on good pastures is less expensive in terms of fossil energy inputs than grain protein production (Table 8.2).

Of the livestock systems evaluated in this investigation, chicken-broiler production is the most efficient with an input of 4 kcal of fossil energy per 1 kcal of broiler protein produced (Table 8.2). Broilers are a grain only system. Turkey production, also a grain only system, is next in efficiency with a ratio of 10:1. Milk production based on a mixture of grain and forage also is relatively efficient with a ratio of 14:1 (Table 8.2). Nearly all the feed protein consumed by broilers is grain, whereas for milk production about two-thirds is grain (Table 8.2). Of course, 100% of milk production could be produced on forage. Both pork and egg production also depend upon grain (Table 8.2). Pork has a 14:1 ratio whereas egg production is relatively more costly in terms of feed energy requiring a 39:1 ratio (Table 8.2).

The two livestock systems depending most heavily on forage, but still using significant amounts of grain, are the beef and lamb production systems (Table 8.2). The lamb system with a ratio of 57:1 and the beef system with a ratio of 40:1 are the two highest (Table 8.2). If these animals were fed only on good quality forage, the energy inputs could be reduced by about half depending on the conditions of the pasture-forage as well as the management practices. Note that beef fed 200 kg of forage and no grain had an energy input per kilocalorie protein output ratio of 20:1 (Table 8.2). Rainfall is critical for all productive pasture systems.

Per kilogram of animal product foods, broiler chicken flesh has the largest percentage of protein and milk the lowest (Table 8.3). Beef has the highest calorie

TABLE 8.3
The Calorie, Water, and Protein Availability per Kilogram of Animal Product

Livestock and Livestock Products	Energy (kcal)	Water (%)	Protein (g)
Lamb	2521	47	220
Beef	2565	49	186
Turkey	1193	55	123
Egg	1469	74	116
Pork	2342	57	134
Dairy	647	87	34
Broiler	1357	71	238

Source: Pimentel, D., Canadian Society of Animal Science, Proceedings, Canadian Society of Animal Science, Montreal, Quebec, 1997. With permission.

content because of its high fat content and relatively low water content. Of all the animal products, milk has the highest water content with 87%.

The average fossil energy input for all animal protein production systems studied is about 25 kcal of fossil energy input per kilocalorie of animal protein produced (Table 8.2). This energy input is more than 10 times greater than the average input to output ratio for grain protein production, which was about 2.5 kcal per kilocalorie of protein produced. As food for humans, however, animal protein has about 1.4 times the biological value as food compared with grain protein.

LAND RESOURCES

Livestock production requires a large number of hectares to supply the grains, forages, and pastures for animal feeds. In fact, nearly 300 million ha of land are devoted to producing the feed for the U.S. livestock population. Of this, 262 million ha are pasture and about 30 million ha are for cultivated grains (USDA, 2001). In addition to the large amount of forages and grass that are unsuitable for human consumption and are fed to animals, about 323 million tons of grains—or about 816 kg per American in the United States—are fed to livestock to provide meat, milk, and eggs (Pimentel and Pimentel, 2003).

More than 99.2% of U.S. food is produced on the land, while less than 0.8% comes from oceans and other aquatic ecosystems (FAO, 1998). The continued use and productivity of the land is a growing concern because of the rapid rate of soil erosion and degradation that is taking place throughout the United States and indeed throughout the world. Each year about 90% of U.S. cropland is losing soil at an average rate 13 times above the sustainable rate of 1 t/ha/year (Pimentel and Kounang, 1998). On croplands where most grain is produced, soil loss averages more than 13 t/ha/year from the combined effects of water and wind erosion. Also, our rangelands are losing soil on an average of 13 t/ha/year (Unnevehr et al., 2003). About 60% of United States rangeland is being overgrazed and is subject to accelerated erosion.

The concern about high rates of soil erosion in the United States and in the world is evident when it is understood that it takes approximately 500 years to replace 25 mm (1 in.) of lost soil (Pimentel and Kounang, 1998). Clearly a farmer cannot wait for the replacement of 25 mm of soil. Commercial fertilizers can replace some nutrient loss resulting from soil erosion, but this requires large inputs of fossil energy (Pimentel et al., 2002).

The future of all agricultural production that requires land, including that targeted for livestock, will feel the effects of land degradation, particularly when fossil fuel supplies decline and prices increase. Soil erosion losses, compounded by salinization and waterlogging, are causing the abandonment of nearly 1 million ha of U.S. agricultural land per year (Troeh et al., 1991; Pimentel and Kounang, 1998). Some of the abandoned, degraded cropland may find use as either pasture or forest.

The costs of soil erosion are well illustrated by the loss of rich U.S. soils. Iowa, which has some of the best soils in the world, has lost more than one-half of its topsoil after only 150 years of farming (Risser, 1981; Klee, 1991). Iowa continues to lose topsoil at an alarming rate of about 30 t/ha/year, which is about 30 times faster than the rate of soil formation (USDA, 1989, 1994). The rich Palouse soils of the Northwest United States have similarly lost about 40% of their topsoil in the past century (Pimentel et al., 1995).

Despite the efforts of the USDA Soil Conservation Service, erosion rates in the United States have decreased only slightly during the past 50 years. This is the result of major changes in agricultural production, such as: emphasis on commodity price-support programs; widespread planting of crop monocultures; crop specialization; abandonment of crop rotations; the removal of tree shelter-belts; leaving the soil without protective biomass cover; and the use of heavy farm machinery (Lal and Stewart, 1990; Pimentel et al., 1995). Concurrently these changes have been accompanied by the creation of fewer and larger farms where increased mechanization is a necessity.

Although modern farming practices are contributing to the soil erosion problem, the failure of farmers and governments to recognize and address the soil erosion problem is equally important if soil depletion is to be halted. Erosion often goes unnoticed by some farmers because soil loss is difficult to measure visually. For instance, one night's wind or rain storm could erode 15 t of soil per hectare as a sheet, which would be only 1 mm of soil; the next morning, the farmer might not even notice this loss. This soil loss continues slowly, quietly, year after year, until the land is no longer productive. In addition, governments tend to ignore erosion because of its insidious nature and because it does not seem to be a major environmental crisis like floods or tornadoes.

WATER RESOURCES

Agricultural production, including livestock production, consumes more fresh water than any other human activity (Postel, 1999). Western U.S. agriculture accounts for about 81% of the fresh water consumed after being withdrawn. Growing plants render all water nonrecoverable through evaporation and transpiration. In the United States, about 62% of the water used in agricultural irrigation comes from surface sources and 38% from ground water sources (Pimentel et al., 1997).

TABLE 8.4
Estimated Liters of Water Required to Produce 1 kg of Food and Forage Crops

Livestock and Crop Products	L/kg
Potatoes	500
Wheat	900
Alfalfa	900
Sorghum	1100
Corn	1400
Rice	1900
Soybeans	2000
Broiler	3500
Beef	43,000

Source: Pimentel, D., Houser, J., Preiss, E., White, O., Fang, H., Mesnick, L., Barsky, T., Tariche, S., Schreck, J., and Alpert, J., *BioScience* 47(2), 97–106, 1997. With permission.

The transfer of water to the atmosphere from the terrestrial environment by transpiration through vegetation is estimated to range between 38% and 65% of the rainfall depending on the terrestrial ecosystem (Pimentel et al., 1997). The vital photosynthetic processes and temperature control necessitate that the plants consume enormous amounts of water.

The water required to produce various food and forage crops range from 500 to 2000 L of water per kilogram of plant biomass produced (Table 8.4). For example, a hectare of U.S. corn producing about 8000 kg per year transpires about 5 million L of water during the growing season. Approximately 1000 mm (10 million L per hectare) of rainfall or other sources of water are needed during the growing season for corn production. Even with 800–1000 mm of annual rainfall in the Corn-Belt region, corn usually suffers from some lack of water during the summer growing season (Troeh and Thompson, 1993).

Producing 1 kg of beef requires about 43 times more water than producing 1 kg of grain (Pimentel and Pimentel, 1996). Livestock directly use only 1.3% of the total water used in agriculture. However, when the water required for forage and grain production is included, this dramatically increases the water requirement for livestock production. Producing 1 kg of fresh beef requires about 13 kg of grain and 30 kg of forage (Table 8.2). This much grain and forage requires a total of 43,000 L of water. On rangeland where an animal consumes about 200 kg of forage to produce 1 kg of beef, about 200,000 L of water are needed to produce the 1 kg of beef (Thomas, 1987). With forage and some cereal crops, livestock can be produced in areas with low rainfall ranging from 150 to 200 mm per year (Rees et al., 1990). However, crop production and yields are low under such conditions.

Animals vary in the amounts of water required for their production. In contrast to beef, 1 kg of broiler chicken can be produced with about 2.6 kg of grain requiring approximately 3500 L of water (Table 8.4).

Water shortages are already severe in the western and southern United States. The situation grows worse as the U.S. population and its requirements for water, including for agriculture, rapidly increase (Pimentel et al., 1999).

WORLD FOOD NEEDS

Worldwide, human food needs are rising and will continue to rise with the world population (Pimentel et al., 1999). Currently, there are more than 3 billion who are malnourished based on shortages of calories, protein, vital minerals, and vitamin in their diets (WHO, 2000). Already there are currently 6.2 billion people on Earth and it is projected that the world population will double, to more than 12 billion in less than 50 years, based on the current growth rate (Pimentel et al., 1999). The U.S. population is also increasing rapidly. The U.S. population is currently at 285 million and is expected to double to 570 million in about 70 years (USBC, 2001). Food security becomes at risk as more and more people need food, while the required resources of land, water, and energy decline per person.

Food consumption patterns in the United States and most other developed nations include generous amounts of animal products. More than half of U.S. grain and nearly 40% of world grain are being fed to livestock rather than being consumed directly by humans. Grains provide 80% of the world's food supply. Although grain production is increasing in total, the per capita supply has been decreasing for nearly two decades (Pimentel and Pimentel, 2003). Clearly, there is reason for concern for the future.

If all the 323 million tons of grain currently being fed to livestock were consumed directly by people, the number of people who could be fed would be approximately 1 billion. Also, if this much grain were exported, it would provide approximately $80 billion each year in income—this is sufficient income to pay for our current oil bill of $75 billion per year (USBC, 2001). Of course, exporting all the grain currently fed to livestock would reduce the average protein consumption of Americans from 112 g per day to approximately 73 g per day. Yet this intake would still be greater than the 56 g of protein suggested by the RDA.

Exporting all U.S. grain that is now fed to livestock assumes that livestock production would change to a grass-fed livestock production system. Animal protein in the diet would then decrease from the current level of 75 g to 36 g per day, or about one-half. Again, the diet for the average American would be more than adequate in terms of protein consumption, provided that there was no change in the current level of plant protein consumed. In fact, consuming less meat, milk, and eggs and eating more grains and vegetables would improve the diet of the average American.

CONCLUSION

Meat, milk, and egg production in the United States relies on significant quantities of fossil energy, land, and water resources. Grain-fed livestock systems use large quantities of energy because grain crops are cultivated; in contrast, cattle grazed on pastures use considerably less energy than grain-fed cattle. An average of 25 kcal of fossil energy is required to produce 1 kcal of animal protein and requires approximately

10 times the energy expended to produce 1 kcal of plant protein. However, it should be noted that animal protein is 1.4 times more nutritious for humans than plant protein.

Nearly one-third of the U.S. land area is devoted to livestock production. Of this, about 10% is devoted to grain production and the remainder is used for forage and range land production. The pastureland and range land are marginal in terms of productivity because there is too little rainfall for crop production.

Livestock production is also a major consumer of water because grains and forage consumed by livestock require significant amounts of water for growth and production. To produce 1 kg of grain requires about 1000 L of water. Based on grain and forage consumption, about 43,000 L of water are required to produce 1 kg of beef. In regions where water is already in short supply and where aquifers are currently being mined faster than they can be recharged, major decisions will have to be made concerning all agricultural production, including grain and forage crops for livestock.

As human food needs escalate along with population numbers, serious consideration must be given to the conservation of fossil energy, land, and water resources. The careful stewardship of these resources is vital if livestock production, and indeed agriculture, will be sustainable for future generations. In the end, population growth must be reduced, in the United States and in the world, if we are to achieve a quality life for ourselves and our grandchildren.

REFERENCES

FAO. 1998. *Food Balance Sheet.* http://armanncorn:98ivysub@faostat.fao.org/lim...ap.pl (November 16, 2000).

Klee, G.A. 1991. *Conservation of Natural Resources.* Englewood Cliffs, NJ: Prentice Hall.

Lal, R. and B.A. Stewart. 1990. *Soil Degradation.* New York: Springer-Verlag.

Pimentel, D. 1997. Livestock production: Energy inputs and the environment. Canadian Society of Animal Science, Proceedings. Canadian Society of Animal Science, Montreal, Quebec.

Pimentel, D. 2006. Soil erosion: A food and environmental threat. *Environment, Development and Sustainability* 8: 119–137.

Pimentel, D., O. Bailey, P. Kim, et al. 1999. Will the limits of the Earth's resources control human populations? *Environment, Development and Sustainability* 1: 19–39.

Pimentel, D., R. Doughty, C. Carothers, et al. 2002. Energy inputs in crop production: Comparison of developed and developing countries. In L. Lal, D. Hansen, N. Uphoff, and S. Slack (eds.), *Food Security & Environmental Quality in the Developing World*, pp. 129–151. Boca Raton, FL: CRC Press.

Pimentel, D., C. Harvey, P. Resosudarmo, et al. 1995. Environmental and economic costs of soil erosion and conservation benefits. *Science* 267: 1117–1123.

Pimentel, D., J. Houser, E. Preiss, et al. 1997. Water resources: Agriculture, the environment, and Society. *BioScience* 47(2): 97–106.

Pimentel, D. and N. Kounang. 1998. Ecology of soil erosion in ecosystems. *Ecosystems* 1: 416–426.

Pimentel, D. and M. Pimentel. 1996. *Food, Energy and Society.* Niwot, CO: Colorado University Press.

Pimentel, D. and M. Pimentel. 2003. Sustainability of meat-based and plant-based diets and the environment. *American Journal of Clinical Nutrition* 78 (suppl.): 660S–663S.

Postel, S. 1999. *Pillar of Sand: Can the Irrigation Miracle Last?* New York: W.W. Norton.

Rees, D.J., A. Samillah, F. Rehman, C.H.R. Kidd, et al. 1990. Precipitation and temperature regimes in upland Balochistan, Pakistan and their influence on rain-fed crop production. *Agricultural Meteorology* 52: 381–396.

Risser, J. 1981. A renewed threat of soil erosion: It's worse than the Dust Bowl. *Smithsonian* 11: 120–130.

Thomas, G.W. 1987. Water: Critical and evasive resource on semiarid lands. In W.R. Jordan (ed.), *Water and Water Policy in World Food Supplies*, pp. 83–90. College Station, TX: College Texas A&M University Press.

Troeh, F.R., J.A. Hobbs, and R.L. Donahue. 1991. *Soil and Water Conservation*. Englewood Cliffs, NJ: Prentice Hall.

Troeh, F.R. and L.M. Thompson. 1993. *Soils and Soil Fertility*. New York: Oxford University Press.

Unnevehr, L.J., F.M. Lowe, D. Pimentel, et al. 2003. *Frontiers in Agricultural Research: Food, Health, Environment, and Communities*. Washington, D.C.: National Academies of Science. 268 pp.

USBC. 2001. *Statistical Abstract of the United States 2001*. Bureau of the Census, Washington, D.C.: U.S. Government Printing Office.

USDA. 1989. *The Second RCA Appraisal. Soil, Water, and Related Resources on Nonfederal Land in the United States. Analysis of Conditions and Trends*. Washington, D.C.: U.S. Department of Agriculture.

USDA. 1994. *Summary Report 1992 National Resources Inventory*. Washington, D.C.: Soil Conservation Service, U.S. Department of Agriculture.

USDA. 2001. *Agricultural Statistics*. Washington, D.C.: U.S. Department of Agriculture.

WHO. 2000. Malnutrition Worldwide. http://www.who.int/nut/malnutrition_worldwide.htm (July 27, 2000).

9 Energy Use in Fish and Aquacultural Production*

David Pimentel, Roland E. Shanks, and Jason C. Rylander

The oceans and other aquatic ecosystems are vital to the sustainability of all life on Earth. In particular, these aquatic systems provide food for humans and livestock. Overfishing and pollution of fresh and saltwater habitats threaten the continued productivity of aquatic systems.

Worldwide, approximately 95 million metric tons of seafood, including fish, crustaceans, and mollusks, are harvested annually (Figure 9.1). About 90% of all harvested fish are from the marine habitat and the remaining 10% from freshwater habitats. About 28 million tons of fish are fed to livestock, and humans consume an estimated 67 million tons (NOAA, 1991). Nonetheless, fish protein represents less than 5% of the total food protein (387 million tons) consumed annually by the world's human population and less than 1% of the overall caloric intake (FAO, 1991).

As with agricultural food production, harvesting fish requires significant quantities of fossil energy (Pimentel, 1980; Scott, 1982; Bardach, 1982, 1991; Billington, 1988; Mitchell and Cleveland, 1993). Because the United States already imports more than half of its oil at a cost of $120 billion/year and proven U.S. oil reserves are projected to be depleted in 20–30 years, this is an appropriate time to analyze the use of energy in fishery production and to determine which fishery systems are the most energy efficient. Energy shortages and high fuel prices likely will influence future fishery policies and the productive capacity of the industry (Samples, 1983; Mitchell and Cleveland, 1993).

The energy inputs, ecological effects, and relative efficiency of a variety of domestic and international fishery regimes are assessed in this chapter. Also included are effects of different types of vessels and gear on the overall efficiency and sustainability of various methods of catching fish.

ECOLOGICAL ASPECTS OF FISH PRODUCTION

Water covers more than 70% of the Earth, but only about 0.03% of the sunlight reaching an aquatic ecosystem is fixed by aquatic plants, primarily phytoplankton (Odum, 1978). This equates to about 4 million kcal/ha/year or about one-third the energy fixed in terrestrial habitats (Pimentel et al., 1978).

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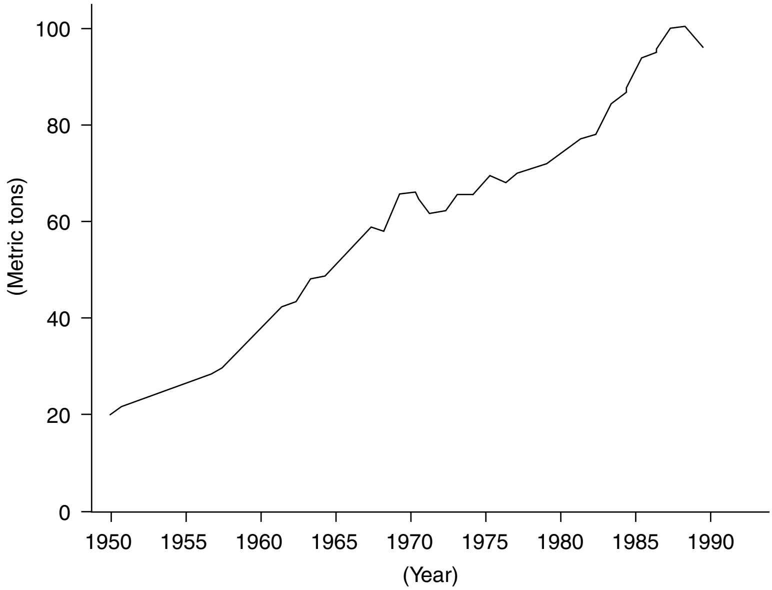

FIGURE 9.1 World fish catch in metric tons per year. (From World Resources Institute, *World Resources 1992–1993*, New York, Oxford University Press, 1992. With permission.)

The phytoplankton that collect light energy in oceans and freshwater are eaten by zooplankton. The light energy passes through four to six links in the food chain before humans harvest it as fish. Energy is dissipated at each link in the food chain, and the final quantity available to humans is much less than that available at the phytoplankton level.

Assuming that each year the ocean ecosystem collects 4 million kcal/ha of light energy and that there are on average four links in the food chain, humans would harvest about 400 kcal/ha/year as fish. Measured in dressed weight of fish, this amounts to only 0.15 kg/ha of harvested fish per year.

If the 115 kg of meat consumed per person per year in the United States were to be supplied by fish from the oceans, and assuming a yield of 0.15 kg/ha of dressed weight (cleaned fish), each person would require nearly 2000 ha of ocean area. Oceans could supply enough fish to meet the needs of only 1.2 billion people. This estimate assumes that the entire fish yield is suitable for human food and that 40% of the catch is edible when cleaned and dressed. Humans actually eat only a few species of fish themselves but feed other fishery products to livestock. Because so many square kilometers of ocean have to be searched for fish, any attempt to increase fish production would be difficult. The farther a vessel must travel from the port, the more energy-intensive the fishing operation.

Overall ecological fishery management will have to be improved, coastal pollution problems solved, and fertilizer nutrient contamination from onshore sources limited if the sea is to remain a viable source of human and livestock food in the future (Bell, 1978; NOAA, 1991).

ENERGY EFFICIENCY OF FISHERY PRODUCTION

The U.S. ocean fishery industry was ranked fifth in the world in 1991 (producing 4.4 million metric tons per year); the former USSR was ranked first (NOAA, 1991). The Alaskan region is the largest U.S. producer, contributing about 56% of the total production by weight; the Gulf of Mexico region is the next largest, providing about 17% of the total (Table 9.1).

Energy expenditures for fishing vary, depending on the distance traveled to harvest and the type of fishing gear used. For example, fishing vessels from Washington state, located relatively near the Alaskan region, use significantly less fuel than do their Japanese counterparts. Wiviott and Mathews (1975) reported that the Washington trawl fleet produced 61.5 kg of fish per liter of fuel, compared with the Japanese production of only 11.4 kg of fish per liter of fuel. They attribute the difference to the fact that the Japanese frequently have to travel long distances for fishing.

Other fishing situations produce different quantities of fish per liter of fuel expended (Table 9.2). For example, Norwegian coastal net fishers produced 13.3 kg

TABLE 9.1
The Total Amounts of Fishery Production in Different Regions of the United States

Region	Thousand Tons	Percentage
Alaska	2450	56
Pacific Coast and Hawaii	300	7
Great Lakes	20	<1
New England	300	7
Mid-Atlantic	90	2
Chesapeake Bay	390	9
South Atlantic	120	3
Gulf	730	17
Total	4400	100

Source: National Oceanic and Atmospheric Administration (NOAA), *Fisheries of the United States 1990*. Washington, D.C., U.S. Government Printing Office, 1991.

TABLE 9.2
Fish Production per Liter of Fuel

Fishing Technology	Fish (kg)
Coastal fishing net and longling (northern Norway)	13.3
Longline (Continental Shelf)	7.0
Factory vessels (United States)	3.4

Source: Bardach, J., in *Handbook of Energy Utilization in Agriculture*. Boca Raton, FL, CRC Press, 1982, 431–440.

of fish per liter of fuel (Bardach, 1982). However, using large factory vessels, they produced only 3.4 kg of fish per liter of fuel. But the Norwegian yield/fuel figure only refers to catching fish, whereas the factory-vessel yield/fuel figure includes both catching and processing.

Another problem in comparing figures for fish produced per liter of fuel is the condition of the fish when weighed. The Norway figure, for example, indicates the weight of fish before processing, but the figure reported for the factory vessel was not qualified and could indicate fish either before or after processing. These issues point to some major problems in assessing the productivity and energy efficiency of the fishery industry. Certainly, the energy inputs for various fisheries differ according to the method of fishing, the type of gear used, the type of vessel used, the level of processing on the vessel, and the geographic region (Schaffer et al., 1989).

ENERGY EFFICIENCY OF OCEAN FISHERIES

Harvesting ocean fish requires ships and diverse types of gear used to search for, capture, and transport the fish. Both the construction and operation of this equipment consumes energy. Although fishing vessels also require human power, this energy input is not large, especially on today's new, heavily mechanized fishing vessels.

The energy input in several different fishing systems is examined below, with detailed analysis of the fishery in the northeastern United States.

NORTHEAST U.S. FISHERY

The location of large fish populations along the continental shelf off the northeastern United States has made this one of the world's most productive fishery regions. Like all food production systems, this fishery cannot operate without energy investments in the form of equipment, fuel, and labor.

Two types of fishing take place in this region: (1) inshore pelagic fishing, which utilizes vessels weighing less than 110 gross registered tons (GRT); and (2) offshore fishing, which employs vessels weighing more than 110 GRT. For the inshore pelagic fishery, an input of only 1.03 kcal of fossil fuel is expended to harvest 1 kcal of fish protein (Rochereau and Pimentel, 1978). Offshore fishery requires an input of 3.9 kcal of fossil energy per kcal of fish protein harvested. Thus, small fishing units are nearly four times more efficient than the larger vessels that travel great distances. The inshore fishery's greater efficiency also is due in part to the more productive fish populations of the inshore region. The inshore fish are mainly zooplankton-eating species, and they are about one-third more efficient than the offshore fishes in storing energy per weight of useable biomass (Rochereau and Pimentel, 1978). The offshore fish are primarily carnivorous and are higher up in the food chain than inshore species.

If unused fish are removed from the reported fish yields, the overall efficiency of the Northeast fishery decreases. The average input/output ratio is 4.1 kcal of fossil energy per kcal of fish protein output (Rochereau and Pimentel, 1978). The inshore fishery expends about 2.2 kcal of fossil energy per kcal of fish protein produced, whereas the offshore fishery requires 9.6 kcal of energy per kcal of fish protein output (Rochereau and Pimentel, 1978).

The U.S. Northeast fishery is relatively efficient by comparison with other fishery systems. For the U.S. fishery industry as a whole, Hirst (1974) reported, about 27 kcal of fossil energy input are required to harvest 1 kcal of fish protein. Leach (1976) reported about 20 kcal of fossil energy input per kcal of fish protein output in the United Kingdom, and Edwardson (1975) reported that steel trawlers operating from Scotland use about 21 kcal of energy per kcal of fish protein harvested. However, Edwardson also reported that the wooden vessels used for inshore fishing require only 2.1 kcal fossil energy input per kcal of fish protein output. This agrees favorably with the 2.2 kcal fossil energy input for the inshore U.S. fishery (Rochereau and Pimentel, 1978).

A major reason for the high efficiency of the Northeast fishing system is that about 93% of the fishing fleet comprises vessels weighing less than 5 GRT (Doeringer et al., 1986). The advantage of using small fishing vessels is illustrated by the following example. Assume an annual yield for the Northeast fishery of 7.6×10^{11} kcal of fish protein and an overall regional fishing capacity of 7 GRT, which is typical of the Northeast fleet. If a fleet of 300-GRT vessels were used instead of the usual small vessels, the input/output ratio would rise from the present 4.1 to about 6.7 kcal fossil energy input per kcal of fish protein harvested (Rochereau and Pimentel, 1978). This represents a 63% decline in energy efficiency. All fishing vessels require energy for construction, maintenance, fuel, and onboard processing.

Overall efficiency declines as the size of the fishing vessel increases because a nonlinear relationship exists between vessel size and gross energy requirements (Rochereau and Pimentel, 1978). For example, 22 vessels of 15 GRT have the same capacity as one 330-GRT vessel; yet the smaller vessels are 44% more energy efficient in obtaining the same fish yield. In general, larger vessels travel farther to fish and use more energy than smaller vessels. For all vessel types, the energy inputs for operating the vessel are the largest of the three energy inputs (construction/maintenance, fuel, and operations). In smaller vessels (7–15 GRT), operating needs significantly dominate energy inputs, whereas in larger vessels the energy expended in construction becomes a major input.

U.S. government policies continue to support the trend toward using larger vessels in the rich Northeast fishery grounds (McGoodwin, 1990; Satchell, 1992), even though such vessels are far less efficient than smaller ones in fossil energy use. Surely this is a questionable policy in view of rising fossil fuel prices and unemployment in the fishing industry (McGoodwin, 1990; Bardach, 1991).

The energy efficiency of the Northeast fishing fleet has been declining steadily since the early 1960s, a decline attributed both to the upsurge of international fishing competition on the Northeast fishing grounds (Bell and Hazleton, 1967; Gulland, 1971, 1974) and to the decline in fish stocks in this fishery region (Smith, 1991). Mitchell and Cleveland (1993) document this in their analysis of the New Bedford, Massachusetts, fisheries (Figure 9.2). For instance, in 1966 the ratio of fossil energy to fish protein kcal was 5:1, whereas by 1989 the ratio had dramatically increased to 35:1.

The development of new integrated fishing technologies (i.e., stern-trawling hydraulic systems and electronic detection systems) has increased fishing efficiency but not the energy efficiency of the vessel (Captiva, 1968; DeFever, 1968; FAO, 1972a; Gulland, 1974; Margetts, 1974). From 1960 to 1964, both the total GRT and the total gross energy expenditures for the Northeast fishery increased (Rochereau

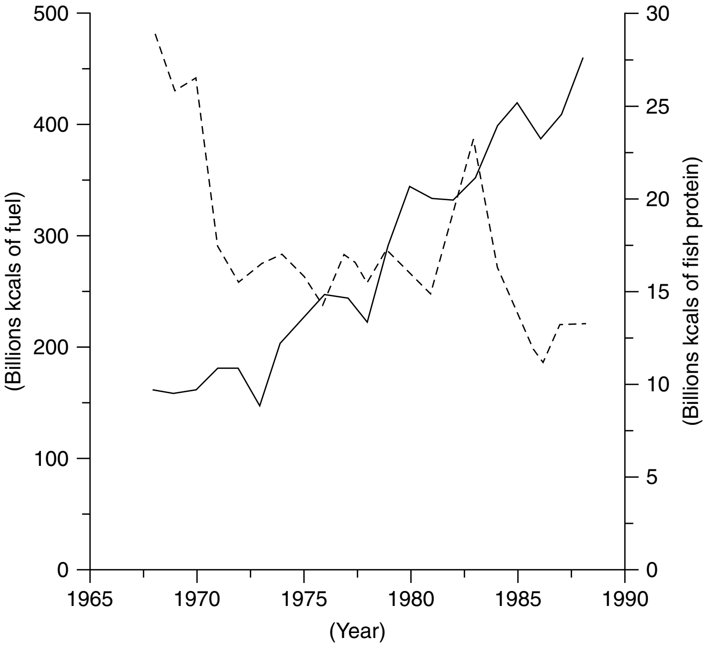

FIGURE 9.2 The total kcal of fish protein caught by the New Bedford, Massachusetts, fleet based on the total amount of fuel used. Fish protein (---) and fuel (——). (From Mitchell, C. and Cleveland, C.J., *Environmental Management*, 17, 305–317, 1993. With permission.)

and Pimentel, 1978). Since 1964 total gross energy expenditures have remained relatively steady, but total GRT has declined sharply. The constancy in total gross energy requirements reflects the replacement of numerous smaller vessels with fewer larger vessels that require more energy both to construct and to operate. Therefore, increasing energy inputs and increasing vessel size have caused deterioration in the energy efficiency of the Northeast fishery industry.

Another major factor contributing to the deterioration of the Northeast fishery is the continued overfishing of the coastal water zone. That is, the yearly harvests are well above the area's maximum sustainable yield level (NOAA, 1992). Of the 49 fishery stocks monitored in the Northeast, 27 have been identified as overexploited (Table 9.3). Large harvests continue because the fishing system in this region is overcapitalized and requires a high level of exploitation to remain profitable (Bell and Hazleton, 1967; Henry, 1971; Gulland, 1971; FAO, 1972b; USDC, 1974). Many scientists believe there is no extra biological stock available to act as a buffer against heavy overfishing (WRI, 1992; NOAA, 1992).

As early as the period from 1967 to 1974, the decline in fish protein production and the increase in fossil energy input reduced the investment return of a typical 50-GRT trawler (Rochereau, 1976). Based on the annual operating cost, which reflects the level of seasonal activity, an inverse relationship exists between the return on the investment and the intensity of fishing in the Northeast (Bell and Hazleton, 1967). That is, as the amount of fishing increases, the return in money

TABLE 9.3
The Exploitation and Status of Monitored Fishery Stocks in the U.S. Northeast

Exploitation Status	Number of Stocks
Overexploited	27
Fully exploited	9
Underexploited	10
Variable exploitation	2
Protected (closed to exploitation)	10

Source: National Oceanic and Atmospheric Administration (NOAA), *Status of Fishery Resources off the Northeastern United States for 1992.* Technical Memorandum NMFS-F/NEC–95. Washington, D.C., U.S. Department of Commerce, 1992.

decreases (Bardach, 1991). Indeed, the Northeast fishery system appears to be approaching the point where the value of the catch will cover only the operating costs; some operations will run in the red. This is beginning to happen, as evidenced by return-on-investment indices. In 1973 the return-on-investment index was more than five times lower than in 1968 for a similar level of effort (Rochereau, 1976). The combined effects of overfishing, rising operating costs, and variable earnings account for the economic instability and the gradual deterioration of the Northeast fishing industry.

U.S. FISHERY

Rawitscher and Mayer (1977) analyzed energy inputs for several types of seafood and estimated that from 2 to 192 kcal of energy were expended per kcal of fish protein produced (Table 9.4). As previously stated, the average for all fish produced for the U.S. market was about 27 kcal of fossil energy per kcal of fish protein produced (Hirst, 1974).

The most efficiently harvested fish is herring, with only 2 kcal of fossil energy expended to produce 1 kcal of herring protein (Table 9.4). A common fish such as haddock requires an input of 23 kcal of fossil energy per protein kcal produced. Lobster requires the largest input—192 kcal of fossil energy per kcal of protein produced. This high energy cost is not surprising considering the relative scarcity of lobsters and the extensive fishing effort that goes into harvesting these animals.

PERU

The anchovy fishing grounds off Peru are one of the most productive fisheries in the world (WRI, 1992). Anchovies are consumed fresh, canned, and as fish meal. In particular, Europe and the United States import large amounts of anchovy fish meal for use in poultry and other livestock production systems.

TABLE 9.4
Energy Input for Production of Various Fish Species in the United States

Seafood Type	Fossil Energy Input/Protein Output (kcal)
Herring	2:1
Perch, ocean	4:1
Salmon, pink	8:1
Cod	20:1
Tuna	20:1
Haddock	23:1
Halibut	23:1
Salmon, king	40:1
Shrimp	150:1
Lobster	192:1

Source: Calculated from Rawitscher, M. and Mayer, J., *Science* 198, 261–264, 1977. With permission.

Leach (1976) gathered data on anchovy and fish meal production in Peru and reported that about 2 kcal of fossil fuel are expended to produce 1 kcal of fish protein. This input is nearly twice the 1.03 kcal of fossil energy needed to produce a kcal of inshore fish protein in the Northeast fishery (Rochereau and Pimentel, 1978). In addition, Leach did not include energy inputs for construction of the vessels, equipment, and fishing gear. As the data from the Northeast fishery system indicate, these inputs are substantial and often represent about half of the total energy used in the system (Rochereau and Pimentel, 1978). If these additional energy costs were included in the Peruvian fish production data, the inshore Northeast fishery would be as much as six times more efficient than Peruvian anchovy fishing.

GULF OF MEXICO AND AUSTRALIA

In comparison with herring, haddock, and anchovies, the production of shrimp in the Gulf of Mexico requires large inputs of energy—about 206 kcal of fossil energy per kcal of shrimp protein produced (Leach, 1976). This ratio is higher than the U.S. average of 150 kcal energy input per kcal of shrimp protein produced (Table 9.4).

Although producing shrimp in the Gulf of Mexico is energy intensive, the investment is profitable at present. Shrimp is considered an extremely choice seafood, and the dollar return is currently high enough to offset the cost of energy expended and other production costs. However, shrimp imported from Asian and South American aquaculture is putting severe economic pressure on the U.S. wild shrimp industry (Coastwatch, 1990; Matherne, 1990).

In the Australian wild shrimp industry, only 22 kcal of fossil energy input are expended to produce 1 kcal of shrimp protein (Leach, 1976). This is significantly less than the U.S. average of 150 kcal and the Gulf of Mexico average of 206 kcal fossil energy input per kcal of shrimp protein harvested.

MALTA

The Malta fishing industry reported an input of 25 kcal of fossil energy per kcal of fish protein produced (Leach, 1976). This input/output ratio of 25:1 is similar to the 27:1 reported for the U.S. fishery and the 20:1 for the U.K. fishery (Hirst, 1974; Leach, 1976).

ADRIATIC

Fish production in the Adriatic region is energy intensive. When small vessels capable of harvesting 50 tons of fish per year were used, the average energy input was about 68 kcal of energy per kcal of fish protein produced (Leach, 1976). However, when large vessels capable of harvesting 150 tons of fish per year were used, the average energy input increased to about 100 kcal of energy per kcal of protein produced.

MARINE FISHERIES AND THE ENVIRONMENT

Serious overfishing of the common species already is a serious problem in many parts of the world, and increased pressure on all kinds of fish populations appears to be the worldwide trend (Satchell, 1992; Worldwatch Institute, 1992). Additional threats to fishery sustainability include: coastal development; loss of coastal wetlands; pollution of bays and estuaries; and bycatch (unintended catch) (Worldwatch Institute, 1992). Consider that almost 50% of the U.S. population now lives within 50 miles of the coastline (Satchell, 1992). Urban development along the coast has infringed on piscatorial breeding grounds and caused massive changes in coastal ecology. For example, Louisiana loses 50 square miles of fish breeding ground each year to development, and only 9% remains of California’s original 3.5 million acres of wetlands (Satchell, 1992). Although some attempt has been made to protect U.S. wetlands, nearly half of them have been drained and used for agricultural or urban development (Satchell, 1992).

All nations, including the United States, have sought ways to protect their fisheries from foreign exploitation. In 1976 the United States asserted an exclusive claim to the sea’s resources within 200 miles of the coast (Sullivan, 1981). The Magnuson Fisheries Conservation and Management Act of 1976 marked the dawning of a new era in fisheries management and eventually decreased the foreign fish catch. Currently, less than 1% of the fish landed from U.S. waters are caught under foreign flags (Park, 2005).

The Magnuson Act created regional committees to implement management programs. Further, it required that fisheries be managed for optimum sustainable yield (OSY), a new concept that is difficult to define. OSY is intended to combine social, economic, ecological, and biological factors into one standard—an extremely difficult task, to say the least (Weber, 1987).

Along with these legal steps has come the use of larger and more modern ships. Concurrently, the number of harbor facilities, processing plants, and fish-handling systems also has increased. Overcapitalization and overcapacity now plague the U.S. fishery industry (Satchell, 1992).

The 1982 Law of the Sea Convention represented the culmination of a series of unilateral declarations of sovereignty over the oceans in the post–World War II era. However, the United States has never signed this agreement. Although some nations were more concerned about oil and mineral rights than fishing, protection of fish from foreign exploitation was a major concern for many nations.

Management of Fishery Systems

Worldwide, small-scale fishing employs about 100 million people, either directly or in supporting industries (McGoodwin, 1990). Large-scale fishing, by contrast, employs only about 500,000 people. The economic contribution of small-scale fishing is increasing (McGoodwin, 1990; Bardach, 1991).

Small-scale fishing is more effective in other ways. For example, its capital cost per job averages 100 times less than that of large-scale fishing (McGoodwin, 1990; Bardach, 1991). It is less likely to be overcapitalized, which is the major problem with many large-scale fisheries today. Small-scale fishing consumes only about 11% of the fuel oil used in commercial fishing, but it produces nearly five times as much fish per unit of fuel oil consumed as the large-scale fishing sector (McGoodwin, 1990; Bardach, 1991).

Most experts agree that the best way to halt overfishing and save the troubled fisheries is to ban all fishing in overexploited areas for 5–10 years. This step has been taken with the cod fishery in Newfoundland, Canada, which recently shut down for 2 years (Worldwatch Institute, 1993). Concurrently, all those who depend on the fishery for their livelihood were placed on welfare (Worldwatch Institute, 1993). This approach works for individual nations' fisheries, but it is doubtful that such a ban would prove effective globally.

The Newfoundland approach is drastic, but the situation is critical. Most fishery management policies have two components: conservation (determining the level of harvest that will ensure the sustainability of the fishery) and allocation (determining who fishes). McGoodwin (1990) identifies seven basic management strategies to achieve sustainability. These include: (1) closing overfished areas for a period of years, as in Newfoundland, to allow the fish populations to come back; (2) establishing closed seasons within each year; (3) establishing aggregate quotas or total allowable catch; (4) restricting gear and technology; (5) using monetary measures such as taxes and subsidies to control fishing; (6) limiting entry in the fishery area; and (7) instituting various forms of property rights over the fishery area.

Gear restrictions and seasonal closings are the traditional methods used to manage fisheries. Many economists dislike these policies because they claim it creates economic inefficiency. However, in certain regions this approach has reduced overfishing and helped maintain the long-term productivity of the fishery (Anderson, 1985). For example, gear restrictions forced New England clam diggers to work only with hand rakes and to harvest only clams above a certain size (Townsend, 1985, 1990; Koppleman and Davies, 1987). As a result, more clam diggers are employed and, more important, the clam population has not been overexploited in New England. These strategies may not be effective in pelagic fisheries unless the number of people fishing in the area is limited as well.

One of the most effective ways to prevent overfishing is to limit access to the fishery. The four major strategies for this are (1) licensing, which limits the number of fishing boats or fishers per area; (2) allocation of quotas by auction to fishers; (3) implementing restrictive taxes or fees that indirectly limit fishing; and (4) establishing a system of catching rights (McGoodwin, 1990; Townsend, 1990; Waters, 1991). A combination of gear restrictions and limited entry has the greatest potential for maintaining the viability of the fishery industry.

With attention and action devoted to preserving the sustainability of fish production, increased quantities of fish could become available for human consumption at decreased energy expense. Certainly, inaction will leave the world fishery in a condition as critical as that now plaguing Newfoundland. Perhaps by more effectively using unexploited fish, implementing sound management of fish populations based on the knowledge of their population ecology, and reducing pollution, the world harvest of fishery products could be improved. However, if the global population doubles in about 47 years, as expected, the percentage of world food calories provided by fish will decline below the present level of less than 1%.

AQUACULTURE

Aquaculture is the farming of fish, shellfish, and other aquatic animals for food (Bardach, 1980). In many regions of the United States, commercial catfish aquaculture is practiced. Catfish is an excellent eating fish, and its popularity has spread throughout the United States.

The largest energy input in catfish aquaculture is the feed. Westoby and Kase (1974) and Mack (1971) reported that catfish required 5.9 tons/ha of feed over the 1.5 years it took them to reach the marketable weight of 0.5 kg per fish. The annual catfish yield was 2783 kg/ha (Table 9.5). The total annual fossil energy input for the

TABLE 9.5
Energy Inputs for Commercial Catfish Production in 1 ha Ponds in Louisiana

	Quantity/ha	kcal/ha
Inputs		
Labor	120 h	63,250
Equipment	9,500,000 kcal	9,500,000
Pumping	1667 kWh	4,343,250
Fertilizer and other chemicals	3.3 kg	60,000
Feed	5925 kg	39,000,000
Total		52,500,500
Outputs		
Catfish yield	2783 kg	
Protein yield[a]	384 kg	1,536,000
Input/Output ratio		34.2:1

[a] Assuming a dressed weight of 60% and 23% protein content.

Source: After Westoby, M. and Kase, R.T., Catfish farming and its economic feasibility in New York state. Unpublished manuscript, Ithaca, NY, 1974; Mack, J., *Catfish Farming Handbook*, San Angelo, TX, Educator Books, 1971. With permission.

production of catfish feed is estimated to be 39 million kcal. The other major energy input for this system is 9.5 million kcal/ha/year for production and maintenance of equipment. An additional 4.3 million kcal is expended to pump and circulate the water in the 1-ha pond. The pumping and circulation of water is necessary to remove wastes and protect the fish from diseases, which are a problem when fish are raised in dense populations. A significant environmental problem is the treatment of the wastewater from catfish production. The U.S. Environmental Protection Agency recently adopted new regulations dealing with wastewater from aquacultural systems, and this will increase the cost of production.

Producing the yield of about 2783 kg/ha/year of catfish requires an input of 52.5 million kcal of fossil energy. Assuming that dressed weight equals 60% of total weight and that protein equals 23% of dressed weight, the total production of catfish protein is 384 kg/ha, equivalent to 1.5 million kcal of food energy. Thus, the input/output ratio is about 34 kcal of fossil energy input per kcal of catfish protein produced. This ratio is identical to that of another U.S. catfish production system (Pimentel et al., 1975) and that of U.S. beef production (Pimentel et al., 1980).

Although catfish are cold-blooded and use no energy in heating their bodies, they are not particularly efficient in converting feed into protein. They are much less efficient than chickens but more efficient than hogs, shrimp, and lobster (Figure 9.3).

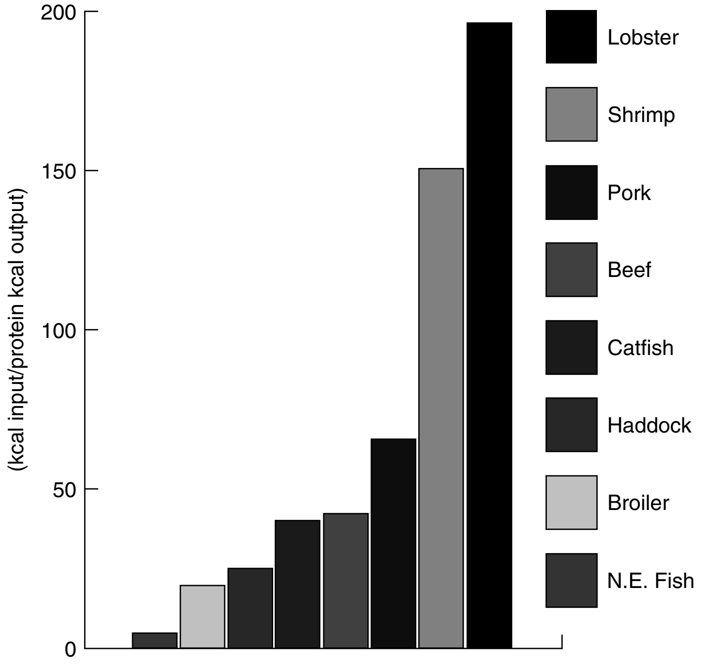

FIGURE 9.3 Fossil energy inputs per protein output for various fisheries and several livestock systems.

TABLE 9.6
Farm Production of Malaysian Prawn (*Macrobrachium rosenbergi*) on Oahu, Hawaii

Item	Amount	kcal
Inputs, fixed		
Pond construction	3.5 ha of land	
Tractor grader	27.5 days/year	1,922,291
Pipes	350 m 6 in. pipe 125 psi	36,120
Cement flumes	120 ft^2 (8 flumes)	238,286
Wooden building	2000 ft^2	217,143
Labor	122 days/year	—
Inputs, annual operating		
Water	130 L/ha/min	—
Labor; manual/miscellaneous	72 days/year	—
Machinery use		
Running maintenance	—	—
Harvesting (50-HP tractor)	91 days/year on 3.5 ha	10,102,698
Materials		
Net	4-cm mesh, 135- × 2-m nylon	7,000
Fertilizer		
Sodium nitrate	14 kg/ha	17,250
Triplesuperphosphate	5 kg/ha	9000
Feed (chicken mash)	4500 kg/ha	9,000,000
Larva for planting (seed)	50,000 larva/ton of production	19,333
Total inputs		21,569,092
Output		
Live Malaysian prawns[a]	3000 kg/ha	3,240,000
kcal input/g protein output		328.3:1
kcal input/kcal output		66.6:1
kcal output/labor hour		129.6:1

[a] Edible portion about 45%; caloric content 720 kcal/kg; protein content in prawn flesh 14.6% (65.7 kg protein from 450 kg of prawn that is edible in 1 metric ton).

Source: Bardach, J., in *Handbook of Energy Utilization in Agriculture*, Boca Raton, FL, CRC Press, 1980, 431–440.

In addition to the catfish system described in detail above, five other aquaculture systems have been analyzed. The first is Malaysian prawn production on Oahu, Hawaii. The fossil energy input per kcal of protein output for this system was about 67:1, or nearly twice that for catfish (Tables 9.5 and 9.6). Prawns, however, have a much higher market value than catfish, and this makes the prawn system profitable.

Oysters were produced through aquaculture on Oahu, Hawaii (Table 9.7). The energy input/output ratio for this system was 89:1, or about one-third higher than that for shrimp production (Table 9.6). The major U.S. oyster-producing regions include Virginia, Maryland, New York, and Connecticut.

TABLE 9.7
Annual Oyster Production on Land in Oahu, Hawaii

Item	Amount	kcal
Water area under production	0.45 ha	
Inputs, fixed		
Farm construction	2,884,436	
Machinery (tractor, grader, dredger)	5 days	
Labor	26 days	72,200
Pipes and cement flumes	3 level, 30 m^3, 1000 m, 6 in. and 4 in. PVC	34,700,000
Plastic trays for oysters	3400 kg	129,956
Inputs, operating		
Seed oysters	—	—
Labor	1095 days	—
Electricity, water pumping	10,000 kWh/month	343,560,000
Fertilizer		
Triplesuperphosphate	5 kg/day/ha	7,391,250
sodium nitrate	20 kg/day/ha	109,500,000
Total inputs		498,237,842
Output		
Oysters[a] (*Grassostrea gigas*)	13,636 kg/ha	5,583,760
kcal input/kcal output		89.2:1
kcal input/g protein output		766.5
kcal output/labor hour		619.9

[a] Edible weight (flesh) 45%; 910 kcal/kg oyster flesh; protein content 10.6%.

Source: Bardach, J., in *Handbook of Energy Utilization in Agriculture*, Boca Raton, FL, CRC Press, 1980, 431–440.

An aquaculture system for lake perch production in Wisconsin proved to be highly energy intensive, with an energy input/output ratio of 189:1 (Table 9.8). It is doubtful that this system will prove economically feasible unless ways are found to reduce energy costs. However, it may become more economical if the fish are raised for sport fishing, because sport fish might have a relatively high market value.

In contrast to U.S. perch production, fish polyculture in Israel has proven to be energy efficient (Table 9.9). Producing an array of species, including the common carp, silver carp, tilapia, and mullet, the polyculture system had an energy input/output ratio of 10:1, making it one of the most efficient aquaculture systems for which data are available. The energy advantage of polyculture is mainly due to its fish-herbivore component—that is, having fish types that feed directly on the plants in the system.

The energetics of an aquacultural system for sea bass and shrimp in Thailand was calculated from data presented by Pillay (1990) and Shang (1992), respectively. The energy input/output ratios for these high-value fishery systems were about 65:1

TABLE 9.8
Experimental Production of Lake Perch (*Perca flavescens*) in Wisconsin

Item	Amount	kcal
Inputs, fixed		
Land	2.08 ha (0.2 ha/ton)	—
Containment structures		
Machinery 50 HP	15.3 days	596,277
Pipes, conduits	1200 m 4 in. PVC, 125 psi	765,217
Buildings	Estimated	1,200,000
Water	3400 m^3/ton	—
Labor	16 days	—
Inputs, operating		
Labor		
Maintenance	250 days	—
Operation	1095 days/year	—
Harvest (for farm)	95 days	—
Nets, pails, etc.	30 × 1 m seine, about 20 kg; dip nets (for farm), 10/20; 1 plastic pail	
Stocking material (fingerlings)	50 kg/ha	4,634,200
Fertilizer	200 kg/ha	3440
Medication	5 kg/ha	350,000
Feed (40% protein dry pellets)	1750 kg/ton of fish	5,250,000
Direct energy inputs	2862-L fuel oil	32,666,868
Pumping	20,190 kWh	57,803,970
Total inputs		103,280,922
Output		
Lake (yellow perch)[a]	per ton	546,000
Protein (19.3%)	115.8 kg protein/ton	891.9
kcal input/kcal output		189.2:1
kcal output/labor hour		181.4

[a] Edible portion 60%; 910 kcal/kg.

Source: Bardach, J., in *Handbook of Energy Utilization in Agriculture*, Boca Raton, FL, CRC Press, 1980, 431–440.

and 70:1, respectively (Tables 9.10 and 9.11). These values are significantly higher than that of the Israeli fish polyculture system and the Louisiana catfish operation (Tables 9.5, 9.9 through 9.11).

In contrast to pond-type aquaculture, marine aquaculture has been tried along the coasts of Norway and Sweden. Atlantic salmon, mass produced in cages, are fed pellets made from fish by-products. These fish pellets represent the consolidation of solar energy fixed by phytoplankton from a sea surface estimated to be 40,000–50,000 times larger than the area of the cages housing the salmon (Folke and Kautsky, 1989, 1992). Low-value fish living over vast areas of the sea are harvested and

TABLE 9.9
Pond Polyculture in Israel

Item	Amount	kcal
Inputs, fixed		
Pond construction	Moving 3000 m^3 of soil	610,000
Pond inlet (steel pipe)	100 m, 20 cm diameter (4100 kg)	2,150,000
Pond outlet		
Asbestos-cement pipe	20 m, 35 cm diameter (35 kg)	3500
Cement base (Monk)	40 kg	3000
Machinery (used on 100 ha for 10 years)	Jeep, tractors, etc., tank cars (22,800 kg of steel)	705,200
Nets (used on 100 ha for 5 years)	200 kg nylon	16,000
Inputs, operating		
Labor	27 days/year	
Machinery operation	Fuel for jeeps, trucks, tractors, aerators, pumping	21,744,000
Fertilizer		
Liquid ammonia	600 L (494 kg N_2)	7,200,000
Superphosphate	600 kg	1,800,000
Herbicide	About 2 kg	99,000
Feed		
Sorghum	4.14 tons	9,108,000
Pellets (25% crude protein)	3.38 tons	6,216,000
Seed production	Prorated from grow-out figs	15,000
Total Inputs		49,670,000
Output		
Production total	4150 kg	4,772,500
Common carp	65.5%	
Silver carp	15.7%	
Tilapia	15.1%	
Mullet	3.7%	
kcal input/kcal output		10.4:1
kcal input/g protein output (unprocessed)		64.7

Source: Bardach, J., in *Handbook of Energy Utilization in Agriculture*, Boca Raton, FL, CRC Press, 1980, 431–440.

concentrated into pellets to feed the high-value caged salmon. This system requires about 50 kcal of fossil energy per kcal of fish protein produced (Folke and Kautsky, 1989, 1992), a figure that compares extremely well with the energy expenditures of other aquacultural systems.

Norway produces more than 40 tons of salmon each year (Folke and Kautsky, 1992). This highly productive system has many economic advantages, but it creates two major environmental problems. The caged Atlantic salmon are not as fit

TABLE 9.10
Energy Inputs and Outputs for Sea Bass Production in Thailand

	Quantity/ha	10^3 kcal/ha
Inputs		
Labor	80 h	47.4
Ponds and operation	50 × 10^6 kcal	50,000
Fuel and lubrication	1890 L	18,900
Feed	35,000 kg	231,000
Total		299,947.4
Outputs		
Sea bass yield	14,000 kg	—
Protein yield	1848 kg	4,600
kcal input/kcal output		65.2:1

Source: Calculated from data presented in Pillay, T.V.R., *Aquaculture Principles and Practices*, Oxford, UK, Fishing New Books, 1990. With permission.

TABLE 9.11
The Energy Inputs in Shrimp Production in Thailand

	Quantity/ha	kcal/ha
Inputs[a]		
Labor	70 h	41,475
Electricity and fuel	31,000,000 kcal	31,000,000
Seed	250 kg	125,000
Feed	6000 kg	24,000,000
Maintenance	14,000,000 kcal	14,000,000
Total		69,500,000
Outputs		
Shrimp yield	2135 kg	
Protein yield	427 kg	1,067,500
kcal input/kcal output		69.5:1

[a] The inputs were calculated from the economic data of Shang Y.C., in *Marine Shrimp Culture: Principles and Practices*, Amsterdam, Elsevier, 1992, 589–604.

for survival in the open sea as the wild Atlantic salmon, and escaped caged salmon sometimes mate with wild salmon, with a negative impact on the overall population. In addition, the heavy concentration of caged salmon along the Norway coast pollutes some of the fjords with fish wastes (T. Edland, personal communication, Ås, Norway, 1992).

CONCLUSION

The Northeast fishery system is generally economical both in terms of energy inputs and dollar returns. By contrast, fishery production systems in the northeastern United States and Gulf of Mexico, such as the lobster and shrimp fisheries, are expensive and require extremely high energy inputs. At present the high market value of these species makes them profitable despite the high costs of harvesting, but these costs make it impractical to treat such fish as a common and abundant food source. Some fish production systems, particularly those in some coastal regions, compare favorably to livestock production systems in terms of energy inputs and efficiency, but others require more energy inputs per kcal of protein produced than livestock systems do.

Small-scale fishing systems are generally more energy efficient than large-scale systems. Especially for developing countries, small-scale fishery systems provide a number of benefits, including increased employment and low fuel costs. Large-scale vessels are inefficient, usually requiring government subsidies for their operation (McGoodwin, 1990). In addition, the high costs of large vessels contribute to overcapitalization and overfishing of fishery resources.

Policymakers have at their disposal a wide range of management techniques to improve fishery production in the future. Gear and season restrictions and limited-access regimes seem to have the greatest potential to protect the biotic stability of the world's fisheries, upon which the future of fish as a food source depends. Long-term sustainability must be the first priority of fishery managers and policymakers.

In the near future, overfishing is more likely to cause fish scarcity than fossil fuel shortages and high energy prices. The causes and seriousness of overfishing and poor management are known. However, at the international and national levels, needed priorities have not been established to deal with the problems. Studies should focus on the breeding habits, population dynamics, and optimal yields of major fish species as well as the effects of pollution on fish habitats to help ensure the sustainability of the major fishery regions. Finding ways to protect wetlands, estuaries, and other aquatic areas will help maintain healthy ecosystems for fish populations.

Concurrently, policymakers need to identify the most efficient type of vessel for each specific region, to encourage development of more energy-effective technologies, and to control harvests. Developing techniques to make effective use of currently unexploited fish will increase the total food harvested from aquatic systems.

However, even if fish production is improved, the rapid growth of the human population will tend to negate the contribution of increased yields. In all probability, the world's fishery industry will not be able to supply more than 1% of the world's food energy in the future. It should be emphasized that fish provide high-quality protein, and thus this 1% is extremely valuable to society.

REFERENCES

Anderson, L.G. 1985. Potential economic benefits from gear restrictions and license limitation in fisheries regulation. *Land Economics* 61: 409–418.

Bardach, J. 1980. Aquaculture. In D. Pimentel (ed.), *Handbook of Energy Utilization in Agriculture*, pp. 431–440. Boca Raton, FL: CRC Press.

Bardach., J. 1982. Oil, fish, and the sun and the wind. In R.C. May, I.R. Smith, and D.B. Thomson (eds.), *Appropriate Technology for Alternative Energy Sources in Fisheries*, pp. 1–6. Manila: International Center for Living Aquatic Resources Management.

Bardach., J. 1991. Sustainable development of fisheries. In International Ocean Institute (ed.), *Ocean Yearbook 9*, pp. 57–72. Chicago, IL: University of Chicago Press.

Bell, F.W. 1978. *Food from the Sea: The Economics and Politics of Ocean Fisheries*. Boulder, CO: Westview Press.

Bell, F.W. and J.E. Hazleton. 1967. *Recent Developments and Research in Fisheries Economics*. New York: Oceana Publications.

Billington, G. 1988. Fuel use control in the fishing industry. In S.G. Fox and J. Huntington (eds.), *World Symposium on Fishing gear and Fishing Vessel Design*, pp. 112–115. St. John's, Canada: Marine Institute.

Captiva, F.J. 1968. Modern U.S. shrimp vessels design, construction, current trends and future developments. In G. DeWitt (ed.), *The Future of the Fishing Industry of the United States*, pp. 141–148. Seattle, WA: University of Washington, Publications in Fisheries, New Series.

Coastwatch. 1990. Shrimping: a fishery in trouble? *Coastwatch* 10: 1–2.

Defever, A. 1968. Modern U.S. tuna vessel construction, design and future trends. In G. DeWitt (ed.), *The Future of the Fishing Industry of the United States*, pp. 134–140. Seattle, WA: University of Washington, Publications in Fisheries, New Series.

Doeringer, P.B., P.I. Moss, and D.G. Terkla. 1986. *The New England Fishing Economy: Jobs, Income, and Kinship*. Amherst, MA: University of Massachusetts Press.

Edwardson, W. 1975. *Energy Analysis and the Fishing Industry*. A Report of the Energy Analysis Unit. Glasgow: University of Strathclyde.

Folke, C. and N. Kautsky. 1989. The role of ecosystems for a sustainable development aquaculture. *Ambio* 18: 234–243.

Folke, C. and N. Kautsky. 1992. Aquaculture with its environment: Prospects for sustainability. *Ocean and Coastal Management* 17: 5–24.

Food and Agriculture Organization (FAO). 1972a. *FAO Catalogue of Fishing Gear Designs*. London: Fishing News (Books) Ltd.

Food and Agriculture Organization (FAO). 1972b. *Atlas of the Living Resources of the Seas*. Rome: Food and Agriculture Organization of the United Nations, Department of Fisheries.

Food and Agriculture Organization (FAO). 1991. *Food Balance Sheets*. Rome: Food and Agriculture Organization of the United Nations.

Gulland, J.A. 1971. *The Fish Resources of the Ocean*. London: Fishing News (Books) Ltd. (for FAO of UN).

Gulland, J.A. 1974. *The Management of Marine Fisheries*. Seattle, WA: University of Washington Press.

Henry, K.A. 1971. *Atlantic Menhaden (Brevoortia tyrannus) Resource and Fishery—Analysis of Decline*. Technical Report, Seattle, WA: National Marine Fisheries Service.

Hirst, E. 1974. Food-related energy requirements. *Science* 184: 134–139.

Koppleman, L.E. and D.S. Davies. 1987. *Strategies and Recommendations for Revitalizing the Hard Clam Fisheries in Suffolk County*. Hauppauge, NY: Suffolk County Planning Department.

Leach, G. 1976. *Energy and Food Production*. Guildford, Surrey, UK: IPC Science and Technology Press Ltd.

Mack, J. 1971. *Catfish Farming Handbook*. San Angelo, TX: Educator Books.

Margetts, A.R. 1974. Modern development of fishing gear. In F.R.H. Jones (ed.), *Sea Fisheries Research*, pp. 243–260. New York: John Wiley & Sons.

Matherne, R. 1990. *Testimony of Concerned Shrimpers of America*. Washington, D.C.: Fisheries and Wildlife Conservation and the Environment Subcommittee of the House of Representative Merchant Marine and Fisheries Committee, U.S. Congress. May 1, 1990.

McGoodwin, J.R. 1990. *Crisis in the World's Fisheries.* Stanford, CA: Stanford University Press.

Mitchell, C. and C.J. Cleveland. 1993. Resource scarcity, energy use and environmental impact: A case study of the New Bedford, Massachusetts, USA, fisheries. *Environmental Management* 17: 305–317.

National Oceanic and Atmospheric Administration (NOAA). 1991. *Fisheries of the United States 1990.* Washington, D.C.: U.S. Government Printing Office.

National Oceanic and Atmospheric Administration (NOAA). 1992. *Status of Fishery Resources off the Northeastern United States for 1992.* Technical Memorandum NMFS-F/NEC–95. Washington, D.C.: U.S. Department of Commerce.

Odum, E.P. 1978. *Fundamentals of Ecology.* New York: Saunders.

Park, J.W. 2005. *Surimi and Surimi Seafood.* Boca Raton, FL: CRC Press.

Pillay, T.V.R. 1990. *Aquaculture Principles and Practices.* Oxford, UK: Fishing New Books.

Pimentel, D. (ed.). 1980. *Handbook of Energy Utilization in Agriculture.* Boca Raton, FL: CRC Press.

Pimentel, D., W. Dritchillo, J. Krummel, et al. 1975. Energy and land constraints in food-protein production. *Science* 190: 754–761.

Pimentel, D., D. Nafus, W. Vergara, et al. 1978. Biological solar energy conversion and U.S. energy policy. *BioScience* 28: 376–382.

Pimentel, D., P.A. Oltenacu, M.C. Nesheim, et al. 1980. The potential for grass-fed livestock: Resource constraints. *Science* 207: 843–848.

Rawitscher, M. and J. Mayer. 1977. Nutritional outputs and energy inputs in seafoods. *Science* 198: 261–264.

Rochereau, S. 1976. Energy analysis and coastal shelf resource management; Nuclear power generation vs. seafood protein production in the Northeast region of the U.S. Ph.D. thesis. Cornell University, Ithaca, NY.

Rochereau, S. and D. Pimentel. 1978. Energy tradeoffs between Northeast fishery production and coastal power reactors. *Journal of Energy* 3: 545–589.

Samples, K.C. 1983. An economic appraisal of sail-assisted commercial fishing vessels in Hawaiian waters. *Marine Fisheries Review* 45: 50–55.

Satchell, M. 1992. The rape of the oceans. *U.S. News and World Report* (June 22): 64–75.

Schaffer, H.C., L.E. Barger, and H.E. Kumpf. 1989. The driftnet fishery in the Fort Pierce–Port Salerno area off southeast Florida. *Marine Fisheries Review* 51: 44–49.

Scott, W.G. 1982. Energy and fish harvesting. In *Proceedings of the Fishing Industry Energy Conservation Conference*, pp. 1–34. New York: Society of Naval Architects and Marine Engineers.

Shang, Y.C. 1992. Penaeid markets and economics. In A.W. Fast and L.J. Lester (eds.), *Marine Shrimp Culture: Principles and Practices*, pp. 589–604. Amsterdam: Elsevier.

Smith, J.W. 1991. The Atlantic and Gulf menhaden purse seine fisheries: Origins, forecasting. *Marine Fisheries Review* 53(4): 20–41.

Sullivan, K. 1981. Overfishing and the new Law of the Sea. *OECD Observer* 129 (July 1991): 16–19.

Townsend, R.E. 1985. An economic evaluation of restricted entry in Maine's soft shell clam industry. *North American Journal of Fisheries Management* 5: 57–64.

Townsend, R.E. 1990. Entry restrictions in the fishery: A survey of the evidence. *Land Economics* 66: 359–378.

U.S. Department of Commerce (USDC). 1974. *Basic Economic Indicators: Atlantic and Pacific Groundfish.* U.S. Department of Commerce, National Atmospheric and Oceanic Administration, National Marine Fisheries Service, Current Fish. Stat. No. 6271.

Waters, J.R. 1991. Restricted access methods of management: Toward more effective regulation of fishing effort. *Marine Review* 53: 1–10.

Weber, M. 1987. Federal marine fisheries management. In R. DiSilvestri (ed.), *Audubon Wildlife Report 1987*, pp. 131–145. San Diego, CA: Academic Press.

Westoby, M. and R.T. Kase. 1974. Catfish farming and its economic feasibility in New York state. Unpublished manuscript, Ithaca, NY.

Wiviott, D.J. and S.B. Mathews. 1975. Energy efficiency comparison between the Washington and Japanese otter trawl fisheries of the Northeast Pacific. *Marine Fisheries Review* 37(4): 21–24.

Worldwatch Institute. 1992. *State of the World 1992*. Washington, D.C.: Worldwatch Institute.

Worldwatch Institute. 1993. *State of the World 1993*. Washington, D.C.: Worldwatch Institute.

World Resources Institute (WRI). 1992. *World Resources 1992–1993*. New York: Oxford University Press.

10 Energy Use in Grain and Legume Production

Worldwide, plants are extremely important sources of calories, protein, and other major nutrients. Indeed, plant foods, especially cereal grains, provide about 80% of the calories and protein consumed by humans.

Recall that some plant foods are also fed to livestock used for human food. Although some plant foods eaten by livestock, such as grasses and forages, are not suitable for human foods, grains and legumes most certainly are. In the United States, about 816 kg of grains and legumes produced per person and suitable for human consumption are diverted to livestock. Almost 90% of the plant calories/protein consumed by humans comes from 15 major crops (Harrar, 1961; Mangelsdorf, 1966; Thurston, 1969): rice, wheat, corn, sorghum, millet, rye, barley, cassava, sweet potato, potato, coconut, banana, common bean, soybean, and peanut.

Cereal grains have always been the dominant source of human food for several reasons. Cereals can be cultured under a wide range of environmental conditions (e.g., soil types, moisture levels, and temperatures), and they yield large quantities of nutrients per unit of land area. In addition, cereals have a relatively low moisture content (13%–15%) at harvest and can be transported more efficiently than potatoes, cassava, and other vegetables, which are about 80% water. The low moisture content of cereals facilitates storage for long periods of time with minimal storage facilities. Finally, most cereal grains sustain only minor damage from pests.

The prime disadvantage of cereal grains is that they contain low levels of lysine, an essential amino acid. Also, dry cereal grains average only about 9% protein, whereas dry legumes average about 20% protein. Most legumes are low in the essential amino acid methionine but high in lysine. Therefore, by eating combinations of cereals and legumes, humans can obtain sufficient quantities of the essential amino acids. In fact, grains and legumes have long been staple foods for people in many areas of the world.

ENERGY INPUTS IN GRAIN PRODUCTION

CORN

Corn is one of the world's major cereal crops. Under favorable environmental conditions, corn is one of the most productive crops per unit area of land. Analysis of energy input and yields must account for the method of corn production: human power, animal power, and full mechanization.

Human power. In Mexico, a single person with an axe and a hoe can produce corn by hand using swidden or cut/burn agricultural technology (Table 10.1).

TABLE 10.1
Energy Inputs in Corn Production in Mexico Using Only Human Power

	Quantity/ha	kcal/ha
Inputs		
Labor	1,144 h[a]	589,160
Axe and hoe	16,570 kcal[b]	16,570
Seeds	10.4 kg[b]	36,608
Total		642,338
Outputs		
Corn yield	1,944 kg[a]	6,901,200
kcal output/kcal input		10.7:1

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

[b] Estimated.

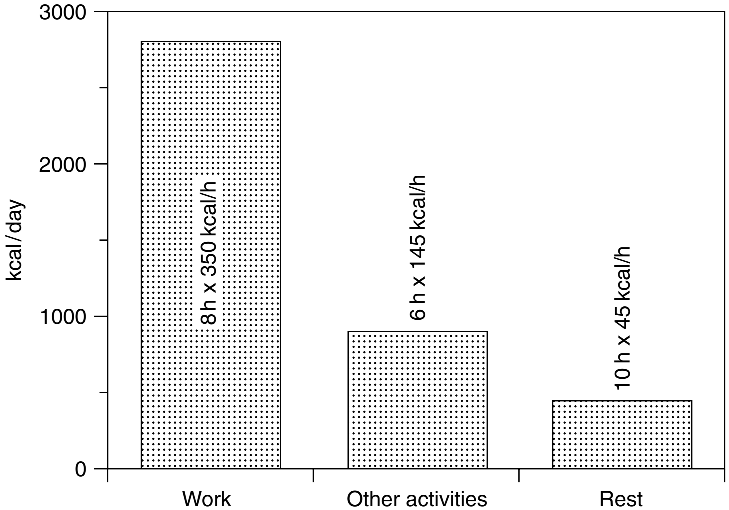

FIGURE 10.1 Total energy expended per adult male in developing countries, in crop-raising activities employing human power only or combined with animal power, is calculated at 4120 kcal per adult male per day.

The total energy input from human labor is 4120 kcal/day (Figure 10.1). Corn production requires about 1140 h (143 days) of labor, an energy expenditure of 589,160 kcal/ha. When the energy for making the axe and hoe and producing the seed is added, the total energy input comes to about 642,300 kcal/ha. With a corn yield of about 1940 kg/ha, or 6.9 million kcal, the energy output/input ratio is about 11:1 (Table 10.1).

In this system, fossil energy is used only in the production of the axe and hoe. Based on a fossil energy input of 16,570 kcal, the output/input ratio is about 422 kcal of corn produced for each kilocalorie of fossil energy expended.

By comparison, producing corn in Guatemala by human power requires about 1420 h/ha, nearly 300 h more than in Mexico (Table 10.2). Moreover, the corn yield is only about 1070 kg/ha, or about half that obtained in Mexico. For these reasons, the output/input ratio is only 5:1, far less efficient than that of Mexico (Table 10.1).

Corn produced in Nigeria by human power requires only 620 h of labor per hectare, about half the labor input required in Mexico and Guatemala (Table 10.3).

TABLE 10.2
Energy Inputs in Corn Production in Guatemala Using Only Human Power

	Quantity/ha	kcal/ha
Inputs		
Labor	1,415 h[a]	728,725
Axe and hoe	16,570 kcal[b]	16,570
Seeds	10.4 kg[b]	36,608
Total		781,903
Outputs		
Corn yield	1,066 kg[a]	3,784,300
kcal output/kcal input		4.84:1

[a] From Stadelman, R., in *Contributions to American Anthropology and History, No. 33*. Carnegie Institute of Washington, Publication 523, 1940, 83–263.

[b] Estimated.

TABLE 10.3
Energy Inputs in Corn Production in Nigeria Using Only Human Power

	Quantity/ha	kcal/ha
Inputs		
Labor	620 h[a]	319,300
Axe and hoe	16,570 kcal[b]	16,570
Nitrogen	11 kg[a]	161,700
Phosphorus	4 kg[a]	12,000
Potassium	6 kg[a]	9,600
Seeds	10.4 kg[b]	36,608
Total		555,778
Outputs		
Corn yield	1004 kg[a]	3,564,200
kcal output/kcal input		6.41:1

[a] From Akinwumi, J.A., *Bulletin of Rural Economists and Sociologists*, Ibadan 6, 219–251, 1971.

[b] Estimated.

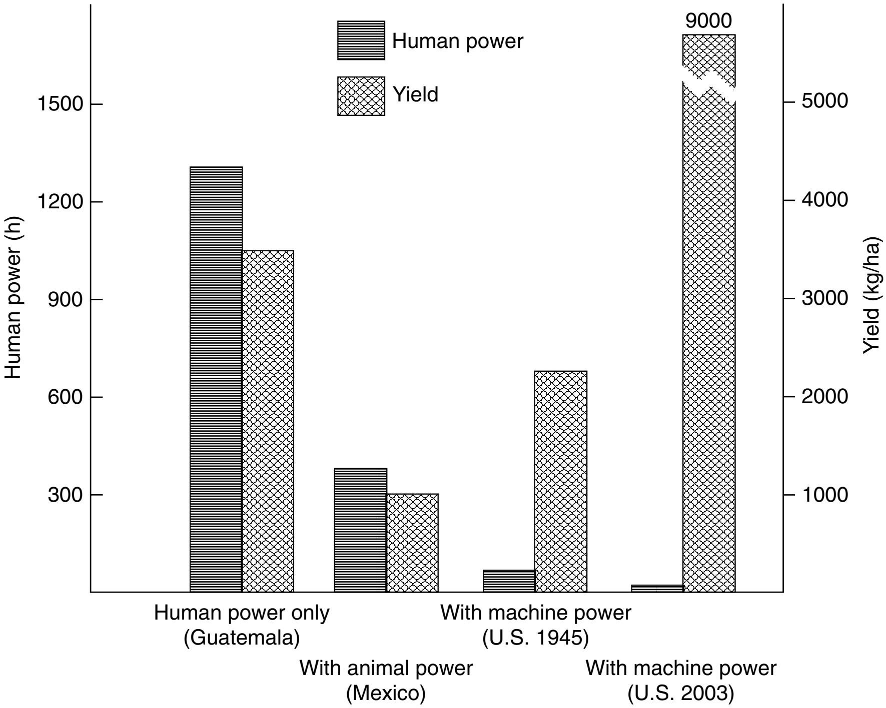

FIGURE 10.2 Human power input and yield per hectare for different corn production systems.

Although Nigerian farmers use a small amount of fertilizer, they produce a corn yield of only about 1000 kg/ha, less than that produced in both Mexico and Guatemala. The output/input ratio, however, is 6:1 because of the relatively low labor input (Table 10.3).

Although the yields of corn produced by hand are significantly lower than yields of corn produced by mechanization in the United States, the reason is not related to the type of power used (Figure 10.2). The lower yields for hand-produced corn can be attributed to the reduced use of fertilizers, lack of hybrid (high-yielding) varieties, poor soil, and prevailing environmental conditions. With the use of suitable fertilizers and more productive varieties of corn, it should be possible to increase crop yields employing only human power.

Draft animal power. In Mexico, about 200 h of oxpower are needed to produce 1 ha of corn. Concurrently, the human labor investment is reduced from about 1140 h to about 380 h (Table 10.4), a savings of about 760 h (Tables 10.1 and 10.4). Under these farming conditions, 1 h of oxpower replaces nearly 4 h of human power.

An ox produces 0.5 to 0.75 HP. One HP-hour of work equals about 10 human hours of work. Thus, 1 oxpower-hour equals 5–7.5 human hours. In Mexico, as noted, 1 oxpower-hour replaces about 4 h of human power (Tables 10.1 and 10.4), slightly lower than the expected 5–7.5 h.

TABLE 10.4
Energy Inputs in Corn (maize) Production in Mexico Using Oxen

	Quantity/ha	kcal/ha
Inputs		
Labor	383 h[a]	197,245
Ox	198 h[a]	495,000[b]
Machinery	41,400 kcal[c]	41,400
Seeds	10.4 kg[c]	36,608
Total		770,253
Outputs		
Corn yield	941 kg	3,340,550
kcal output/kcal input		4.34:1

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

[b] Assumed 20,000 kcal of forage consumed per day by ox.

[c] Estimated.

Assuming that an ox consumes about 20,000 kcal/day in forage and grain (Pimentel, 1974) and that a human consumes 4120 kcal/day at hard work, raising crops with draft animals requires more energy input than raising crops by hand (Tables 10.1 and 10.4). It should be re-emphasized, however, that oxen consume mostly forage, which is unsuitable for human consumption.

The total energy input for human/ox corn production is about 770,253 kcal/ha, for an output/input ratio of about 4:1. This low ratio is due to a reduced corn yield, which is less than half (about 940 kg/ha) the yield obtained by human power alone (about 1940 kg/ha) (Table 10.4). One possible reason for this low productivity is that the corn is planted on heavily farmed bottomland. In all probability the fertility of the soil on this bottomland is lower than that in the swidden areas. If leaves and other organic matter were added to the soil each season, the corn yields might equal those of the swidden culture, but additional labor would be needed to gather, transport, and spread this material.

In Guatemala, the use of about 310 h of oxpower reduces the human labor input almost by half (Table 10.5). Human/ox production requires a greater food energy input (1.2 million kcal) than hand production (781,900 kcal), but the corn yields are the same. Thus, the 3:1 output/input ratio for human/ox production is lower than that for human power alone.

When carabao draft animals are used for corn production in the Philippines, the human and animal inputs are similar to those for Mexico (Table 10.6). The corn yield is also similar, even though some fertilizer is used in the Philippines. It is somewhat surprising to find such close similarity in both input and output between two systems located in geographically and culturally different parts of the world.

Machine power. The energetics of mechanized agriculture is distinctly different from that of labor-intensive agriculture. Corn production in the United States is a typical example of machine-driven agriculture. As expected, the total input of

TABLE 10.5
Energy Inputs in Corn Production in Guatemala Using an Ox

	Quantity/ha	kcal/ha
Inputs		
Labor	700 h[a]	360,500
Ox	311 h[a]	777,500[b]
Machinery	41,400 kcal[c]	41,400
Seeds	10.4 kg[c]	36,608
Total		1,216,008
Outputs		
Corn yield	1066 kg[a]	3,784,300
kcal output/kcal input		3.11:1

[a] From Stadelman, R., in *Contributions to American Anthropology and History, No. 33*. Carnegie Institute of Washington, Washington, D.C., Publication 523, 1940, 83–263.

[b] Assumed 20,000 kcal of forage consumed per day by ox.

[c] Estimated.

TABLE 10.6
Energy Inputs in Corn Production in the Philippines

	Quantity/ha	kcal/ha
Inputs		
Labor	296 h[a]	152,440
Carabao	182 h[a]	364,325[b]
Machinery	41,400 kcal[c]	41,400
Nitrogen	4 kg[a]	58,800
Phosphorus	1 kg[a]	3,000
Potassium	0.3 kg[a]	480
Seeds	10.4 kg[c]	36,608
Transportation	3,000 kcal	3,000
Total		660,053
Outputs		
Corn yield	941 kg	3,340,550
kcal output/kcal input		5.06:1

[a] From AED, *Cost of Production of Corn*. Manila, Department of Agriculture and National Resources, 1960; Food and Agriculture Organization (FAO), *Agriculture: Toward 2000*, Rome, Food and Agriculture Organization of the United Nations, 1981; Allan, P., *Span*, 4, 32–35, 1961.

[b] Assumed 20,000 kcal of forage consumed per day by ox.

[c] Estimated.

TABLE 10.7
Energy Inputs in U.S. Corn Production

	Quantity/ha	kcal/ha
Inputs		
Labor	11.4 h	4,650
Machinery	55 kg	1,018,000
Diesel	88 L	1,003,000
Gasoline	40 L	405,000
Nitrogen	153 kg	2,448,000
Phosphorus	65 kg	270,000
Potassium	77 kg	251,000
Limestone	1120 kg	315,000
Seeds	21 kg	520,000
Irrigation	8.1 cm	320,000
Insecticides	2.8 kg	280,000
Herbicides	6.2 kg	620,000
Electricity	13.2 kWh	34,000
Transportation	204 kg	169,000
Total		8,115,000
Outputs		
Corn yield	8655 kg	31,158,000
kcal output/kcal input		3.84:1

Source: Pimentel, D. and Patzek, T., *Natural Resources Research*, 14(1), 65–76, 2005.

human power is dramatically reduced compared to the systems previously discussed, averaging 11.7 h/ha (Table 10.7). The total energy input per 8-h day for human labor is calculated to be 3720 kcal/ha (Figure 10.3). Therefore, 11.7 h of labor represents a total energy input of 4650 kcal, substantially less than that expended in any of the agricultural systems previously discussed.

Balanced against this low human power input is the significant increase in fossil energy input needed to run the machines. In the United States in 2003, fossil fuel energy inputs averaged about 8.1 million kcal/ha of corn, the equivalent of about 8100 L of gasoline. The corn yield is also high, about 8655 kg/ha, or the equivalent of 31 million kcal/ha of energy, resulting in an output/input ratio of about 3.8:1.

Since 1945 total energy inputs in U.S. corn production have increased more than fourfold, while the output/input ratio remains about the same. During this period fossil fuel has been relatively cheap, so the decline in energy ratios has not reduced the economic benefits received from the high corn yields from intensive production.

The fossil energy inputs into U.S. corn production are primarily from petroleum and natural gas. Nitrogen fertilizer, which requires natural gas for production, represents the largest single input, about 30% of the total fossil energy inputs (Table 10.7).

Machinery and fuel together total about 25% of the total fossil energy input. About 25% of the energy inputs in U.S. corn production are used to reduce human and animal labor inputs, the remaining 75% to increase corn productivity.

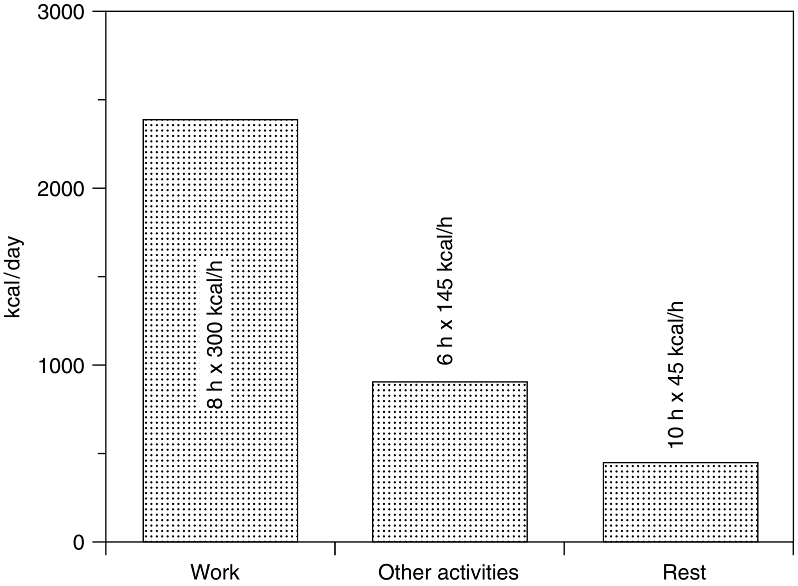

FIGURE 10.3 Total energy expended per U.S. adult male in crop-raising activities employing machinery is calculated at 3720 kcal per day.

WHEAT

Wheat is the single most important cereal crop grown in the world today. More humans eat wheat than any other cereal grain. Wheat is produced in diverse systems with energy sources ranging from human/animal power to heavy machines. As with corn production, energy inputs and yields vary with each wheat production system and therefore influence ultimate output/input ratios.

For example, wheat farmers in the Uttar Pradesh region of India use human/bullock power (Table 10.8). A total energy input of about 2.8 million kcal/ha is required to attain a wheat yield of 2.7 million kcal/ha of food energy, for an output/input ratio of 0.96:1. Thus, the wheat energy produced is less than the energy expended, and the system appears to create no net gain. However, this output/input ratio may be somewhat misleading, because one of the largest inputs in this production system (2.2 million kcal/ha) is for the two bullocks (Table 10.8). Because the bullocks consume primarily grasses and little or no grain, they are in fact a type of food conversion system. The bullocks convert the grass energy into wheat energy through their labor in the wheat fields. If the bullock input is removed from the analysis, then the output/input ratio increases to 5:1, which is a more favorable and realistic representation of this mode of production.

The only fossil energy input in this human/bullock system is that expended for machinery. The ratio of output to fossil energy input is an efficient 65:1 (Table 10.8).

In contrast with the relatively simple Indian production system, wheat production in the United States requires many more energy inputs (Table 10.9). Large machinery powered by fossil energy replaces animal power and drastically cuts human labor inputs. The machinery and use of fertilizers, though increasing the wheat yield per

TABLE 10.8
Energy Inputs in Wheat Production Using Bullocks in Uttar Pradesh, India

	Quantity/ha	kcal/ha
Inputs		
Labor	615 h[a]	324,413
Bullock (pair)	321 n[a] (each)	2,247,500[b]
Machinery	41,400 kcal[c]	41,400
Manure	Included in labor and bullock	
Irrigation	Included in labor and bullock	
Seeds	65 kg[c]	214,500
Total		2,827,813
Outputs		
Wheat yield	821 kg[a]	2,709,300
kcal output/kcal input		0.96:1

[a] Ministry of Food, Agriculture Community Development and Cooperation (MFACDCGI), *Farm Management in India*, New Delhi, Directorate of Economy and Statistics, Department of Agriculture, Government of India, 1966.

[b] Assumed each bullock consumed 20,000 kcal of forage per day.

[c] Estimated.

TABLE 10.9
Energy Inputs in U.S. Wheat Production in the United States

	Quantity/ha	kcal/ha
Inputs		
Labor	7.8 h	316,000
Machinery	50 kg	800,000
Diesel	49.5 L	565,000
Gasoline	34.8 L	352,000
Nitrogen	68.4 kg	1,272,000
Phosphorus	33.7 kg	140,000
Potassium	2.1 kg	7,000
Seeds	60 kg	218,000
Insecticides	0.05 kg	5,000
Herbicides	4 kg	400,000
Fungicides	0.004 kg	400
Electricity	14.3 kWh	41,000
Transportation	197.9 kg	123,000
Total		4,239,000
Outputs		
Wheat yield	2,670 kg	9,035,000
kcal output/kcal input		2.13:1

Source: Pimentel, D., http://www.organic-center.org/science.pest.php?action=view&report_id=59, August 2006.

TABLE 10.10
Energy Inputs in U.S. Oats Production in Minnesota

	Quantity/ha	kcal/ha
Inputs		
Labor	3.2 h	1,500
Machinery	7.7 kg	139,000
Diesel	30 L	337,000
Gasoline	20 L	198,000
Nitrogen	56 kg	824,000
Phosphorus	26 kg	79,000
Potassium	17 kg	27,000
Seeds	108 kg	430,000
Herbicides	0.6 kg	56,000
Transportation	155 kg	40,000
Total		2,129,500
Outputs		
Oat yield		10,897,500
kcal output/kcal input		5.1:1

Source: Weaver, S.H., in *Handbook of Energy Utilization in Agriculture*, CRC Press, Boca Raton, FL, 1980, 85–92.

hectare, also significantly increase the use of fossil fuel energy over that expended in the human/bullock system. Overall, a 4.2 million kcal/ha energy input produces 59.0 million kcal/ha of wheat energy in U.S. production, a 2.1:1 ratio.

OATS

In the United States, oats are a highly productive grain crop (Table 10.10). In an average year, 2.1 million kcal/ha energy inputs yield 10.9 million kcal of oats. The output/input ratio, therefore, is 5:1 or higher than that for wheat. As with U.S. wheat production, the human labor input per hectare is relatively small, whereas fossil fuel to run machines is one of the major energy inputs.

RICE

Rice is the staple food for an estimated 3 billion people, mostly those living in developing countries. This heavy consumption makes an analysis of various techniques used in rice production particularly relevant.

The rice production system used by the Iban tribe of Borneo illustrates cultivation by hand (i.e., using only human power) (Table 10.11). Freeman (1955) reported that the Iban expend a total of 1186 h of human labor per hectare of rice (Table 10.11). In this swidden production system, farmers cut and burn both virgin and secondary forest growth for subsequent rice cultivation. Energy inputs per hectare of rice total 1 million kcal, with about two-thirds of this total representing human labor

TABLE 10.11
Energy Inputs in Rice Production for the Iban of Borneo Using Only Human Power

	Quantity/ha	kcal/ha
Inputs		
Labor	1,186 h[a]	625,615
Axe and hoe	16,570 kcal[b]	16,570
Seeds	108 kg[b]	392,040[c]
Total		1,034,225
Outputs		
Rice yield	2,016 kg[a]	7,318,080
kcal output/kcal input		7.08:1

[a] From Freeman, J.D., *Iban Agriculture*, London, Her Majesty's Stationery Office, 1955.

[b] Estimated for construction of axe and hoe.

[c] Estimated and direct food energy content of rice used in planting.

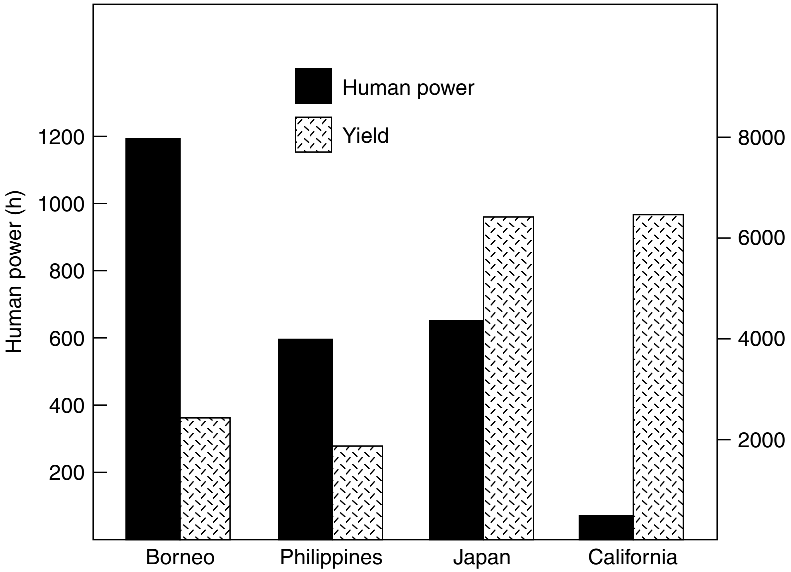

FIGURE 10.4 Human power input and yield per hectare for rice production systems in Borneo (human power only), Philippines (with animal power), Japan (with machine power), and California (with machine power).

and the other one-third representing seeds. The yield is about 2020 kg/ha, or about 7.1 million kcal/ha of food energy. Thus, the output/input ratio is 7.1:1, a relatively high return for the investment.

As in corn production, yields decline as human labor input increases, except in Japan and China (Figure 10.4). In those countries, high yields of rice can be grown

TABLE 10.12
Energy Inputs in Rice Production in Japan

	Quantity/ha	kcal/ha
Inputs		
Labor	640 h[a]	297,600
Machinery	44 kg[b]	860,000
Fuel	90 L[c]	909,810
Nitrogen	190 kg[b]	2,800,000
Phosphorus	90 kg[b]	300,000
Potassium	88 kg[d]	140,800
Seeds	112 kg[e]	813,120
Irrigation	90 L[c]	909,810
Insecticides	4 kg[c]	400,000
Herbicides	7 kg[c]	700,000
Electricity	2.6 kWh[c]	7400
Transportation	300 kg[c]	82,500
Total		8,221,040
Outputs		
Rice yield	6330 kg[f]	22,977,900
kcal output/kcal input		2.80:1

[a] Murugaboopathi, C., M. Tomita, E. Yamaji, et al., *Trans. ASAE* 34(5), 2040–2046, 1991.

[b] Hashimoto, K., A.M. Heagler, and B. McManus, *Agricultural Economics and Agribusiness* 106, 1992.

[c] Estimated.

[d] From Allan, P., *Span* 4, 32–35, 1961.

[e] Estimated from Grant, W.R. and T. Mullins, *Arkansas Agricultural Experimental Station Reports Series* 119, 1963.

[f] From U.S. Department of Agriculture (USDA), *Agricultural Statistics 1991*, Government Printing Office, Washington, D.C., 1991.

employing human power because appropriate high-yielding varieties, fertilizers, and other technologies are used (Table 10.12).

In the Philippines, both human and animal power are used in rice production (Table 10.13). Total energy inputs of 1.8 million kcal/ha produce 1650 kg/ha of rice, which has the equivalent of 6.0 million kcal of food energy. The resulting output/input ratio is 3:1, about half that of the Iban rice production system. However, like the bullocks used for wheat production in India, the Philippine carabao used in rice production convert grass energy into rice energy. If the energy input for the carabao is removed from the accounting, the output/input ratio rises to 10:1.

As with other grains, the United States uses large inputs of energy, particularly fossil fuel energy, to produce rice (Table 10.14). Based on data from rice production in the United States, the average yield is 7367 kg/ha (26.5 million kcal), significantly greater than yields from the other systems discussed. However, the high energy input of 11.8 million kcal/ha results in a low 2.2:1 output/input ratio. Although most of the

TABLE 10.13
Energy Inputs in Rice Production in the Philippines Using Carabao

	Quantity/ha	kcal/ha
Inputs		
Labor	576 h[a]	303,840
Equipment	41,424 kcal[b]	41,424[b]
Carabao	272 h[a]	952,000[c]
Nitrogen	5.6 kg[a]	85,008
Seeds	108 kg[a]	399,600[d]
Herbicide	0.6 kg[a]	43,560
Total		1,825,432
Outputs		
Rice yield	1654 kg[a]	6,004,020[e]
kcal output/kcal input		3.29:1

[a] From De Los Reyes, B.N., E.V. Quintana, R.D. Torres, et al., *Philippine Agriculture* 49, 75–94, 1965.

[b] Estimated for machinery.

[c] Inputs for carabao were assumed to be similar to that for oxen.

[d] De Los Reyes et al. (1965) valued rice seed at 3700 kcal/kg.

[e] White rice contains 3630 kcal/kg.

Source: Pimentel, D., in *Enciclopedia della Scienza e della Tecnica*, Mondadori, Milan, 1976, 251–266.

TABLE 10.14
Energy Inputs in U.S. Rice Production in the United States

	Quantity/ha	kcal/ha
Inputs		
Labor	24 h	972,000
Machinery	38 kg	742,000
Diesel	225 L	2,573,000
Gasoline	55 L	558,000
Nitrogen	150 kg	2,789,000
Phosphorus	49 kg	203,000
Potassium	56 kg	183,000
Sulfur	20 kg	30,000
Seeds	180 kg	772,000
Irrigation	250 cm	2,139,000
Insecticides	0.1 kg	10,000
Herbicides	7 kg	700,000
Fungicides	0.16	16,000
Electricity	33 kWh	85,000
Transportation	451 kg	116,000
Total		11,838,000

(*continued*)

TABLE 10.14 (continued)
Energy Inputs in U.S. Rice Production in the United States

	Quantity/ha	kcal/ha
Outputs		
Rice yield	7367 kg	26,522,190
kcal output/kcal input		2.24:1

Source: Pimentel, D. http://www.organic-center.org/science.pest.php?action=view&report_id=59, August 2006.

TABLE 10.15
Energy Inputs in Sorghum Production in the Sudan Using Primarily Human Power

	Quantity/ha	kcal/ha
Inputs		
Labor	240 h[a]	126,600
Hoe	16,570 kcal[b]	16,570
Seeds	19 kg[b]	62,700
Total		205,870
Outputs		
Sorghum yield	900 kg[a]	2,970,000
kcal output/kcal input		14.43:1

[a] Bureau pour le Development de la Production Agricole (BDPA), *Techniques Rurales en Afrique. Les temps de traux*, Republique Française, Ministère de la Cooperation, 1965.

[b] Estimated.

energy input is for machinery and fuel, fertilizers account for about 50% of the total fossil fuel input. The other inputs are for irrigation, seeds, and drying. The human labor input is only 24 h/ha, still a relatively high figure for U.S. grain production.

By comparison, rice production in Japan is still relatively labor intensive, requiring about 640 h/ha of human labor (Table 10.12). Fossil energy inputs are lower in Japan than in the United States, but rice yields in the two countries are about the same. As a result, Japanese production methods achieve an output/input ratio of 2.8:1, reflecting a more efficient use of energy than the U.S. system.

SORGHUM

Sorghum is used extensively in Africa for food. The available data indicate that producing sorghum by hand in the Sudan requires less human power than does producing corn by hand in Mexico. Sorghum production in the Sudan requires only 240 h/ha (Table 10.15) versus about 1140 h/ha for corn production in Mexico (Table 10.1). Human power is the major energy input, more than half of the total. The hoe represents the system's only fossil energy input, costing only about 16,570 kcal. With

TABLE 10.16
Energy Inputs per Hectare in U.S. Sorghum Production

	Quantity/ha	kcal/ha
Inputs		
Labor	12 h[a]	5580
Machinery	31 kg[b]	558,000[b]
Diesel	135 L[a]	1,540,890
Nitrogen	78 kg[c]	1,146,600
Phosphorus	31 kg[c]	93,000
Potassium	10 kg[d]	16,000
Limestone	30 kg[a]	9450
Seeds	30 kg[a]	420,000[g]
Irrigation	625,000 kcal[d]	625,000
Insecticides	1 kg[e]	86,910
Herbicides	4.5 kg[e]	449,595
Electricity	380,000 kcal[f]	380,000
Transportation	162 kg	41,634[h]
Total		5,372,659
Outputs		
Sorghum yield	3031 kg[e]	10,547,880
kcal output/kcal input		1.96:1

[a] Estimated.

[b] An estimated 31.4 tons of machinery is used to manage about 100 ha, and it is assumed that the machinery depreciates over 10 years.

[c] U.S. Department of Agriculture (USDA), *Economic Research Service, Report No. FS–4*. Washington, D.C., 1974.

[d] An estimated 4% of sorghum was irrigated.

[e] Based on U.S. Department of Agriculture (USDA), *Economic Research Service, Report No. FS–4*. Washington, D.C., 1975.

[f] Electrical use was assumed to be 380,000 kcal/h.

[g] From Heichel, G.H., in *Handbook of Energy Utilization in Agriculture*, CRC Press, Boca Raton, FL, 1980, 27–33.

[h] 162 kg × 257 kcal/kg.

a yield of 900 kg/ha, or 3 million kcal/ha, the resulting output/input ratio is 14:1, a relatively high production ratio.

Sorghum production in the United States requires large inputs of energy, mainly fossil energy used in making and running machines and for producing fertilizer (Table 10.16). Thus, although the 3031 kg/ha yield is more than three times greater than that of the Sudan, the final output/input ratio of 2:1 is significantly lower.

The inputs are lower for sorghum than for corn in the United States (Tables 10.7 and 10.16), but the yield is also considerably lower (3031 kg/ha for sorghum versus 7500 kg/ha for corn). One reason for the lower sorghum yield is that sorghum is produced mainly in dry regions, whereas corn is grown in areas that have moisture conditions more suitable for growing crops.

ENERGY INPUTS IN LEGUME PRODUCTION

Peas, beans, and lentils, all members of the Leguminosae family, are extremely important plant foods, especially in those areas of the world where animal foods are scarce and expensive or where religious or cultural reasons dictate the avoidance of animal flesh as food. Most legumes have a high carbohydrate content of 55%–60% and a high protein content of 20%–30%. The 30% protein content of soybeans is exceptionally high for plants. Legumes are excellent plant sources of iron and thiamine in addition to protein.

SOYBEANS

Owing to its high protein content, the soybean is probably the single most important protein crop in the world. About two-thirds of all soybeans produced are grown in the United States, China, and Brazil. In the United States, relatively little of the soybean crop is used as human food. Instead, the bean is processed for its valuable oil, and the seed cake and soybean meal are fed to livestock. Soybeans and soy products head the list of U.S. agricultural exports (USDA, 2003) and therefore are an important factor in the U.S. balance of export/import payments.

In the United States, soybean yields an average in food energy amounting to 9.6 million kcal/ha (Table 10.17). Production inputs total 3.7 million kcal/ha, so the output/input ratio is 2.6:1. The two largest inputs are for lime and seeds, the third

TABLE 10.17
Energy Inputs in U.S. Soybean Production

	Quantity/ha	kcal/ha
Inputs		
Labor	7.1 h	284,000
Machinery	20 kg	360,000
Diesel	38.8 L	442,000
Gasoline	35.7 L	270,000
LP Gas	3.3 L	25,000
Nitrogen	3.7 kg	59,000
Phosphorus	37.8 kg	156,000
Potassium	14.8 kg	48,000
Lime	2,240 kg	616,000
Seeds	69.3 kg	554,000
Herbicides	1.3 kg	130,000
Electricity	10 kWh	29,000
Transportation	154 kg	40,000
Total		3,013,000
Outputs		
Soybean yield	2668 kg	9,605,000
kcal output/kcal input		3.19:1

Source: Pimentel, D., http://www.organic-center.org/science.pest.php?action=view&report_id=59, August 2006.

largest for manufacturing the machinery. Note that the yield of protein is higher for soybeans than for any other legume tabulated.

Legumes need less nitrogen than most other crops. For example, soybeans require only one-tenth the nitrogen input needed for corn (Tables 10.7 and 10.17). Soybeans and other legumes obtain nitrogen from the atmosphere through their symbiotic relationship with microbes in the soil. The nitrogen-fixation process carried on by the microbes uses about 5% of the light energy captured by the soybean plants, but it saves on energy used for fertilizer. Supplying 100 kg of commercial nitrogen fertilizer to replace the nitrogen fixed by legumes would necessitate the expenditure of 1.6 million kcal of fossil energy. Overall, it is more economical for plants to provide their own nitrogen than for humans to make and apply nitrogen fertilizer. The 100 kg of soybean yield that is lost to nitrogen fixation is worth about $9.25, much less than the $58 cost of the 100 kg/ha of nitrogen produced by the plants.

DRY BEANS

The energy inputs for the production of dry beans are quite similar to those for soybeans (Table 10.18). Average dry bean yields of 1457 kg/ha are lower, however, than

TABLE 10.18
Energy Inputs in U.S. Dry Bean Production

	Quantity/ha	kcal/ha
Inputs		
Labor	10 h[a]	4,650
Machinery	20 kg[b]	360,000[b]
Diesel	76 L[b]	867,464
Nitrogen	16 kg[c]	235,200
Phosphorus	18 kg[c]	54,000
Potassium	47 kg[c]	75,200
Lime	350 kg[a]	110,250
Seeds	60 kg[a]	480,000[d]
Insecticides	1 kg[b]	86,910
Herbicides	4 kg[b]	399,640
Electricity	10 kWh[a]	28,630[a]
Transportation	148 kg	38,036[d]
Total		2,739,980
Outputs		
Dry bean yield	1,457 kg[e]	4,953,800
kcal output/kcal input		1.81:1

[a] Estimated from soybean data.

[b] Estimated.

[c] Assumed to be similar to U.S. soybean production.

[d] 148 kg × 257 kcal/kg.

[e] From U.S. Department of Agriculture (USDA), *Agricultural Statistics 1976*, Government Printing Office, Washington, D.C., 1976.

TABLE 10.19
Energy Inputs in North-Central Nigerian Cowpea Production

	Quantity/ha	kcal/ha
Inputs		
Labor	814 h[a]	419,210
Hoe and other equipment	16,570 kcal[b]	16,570[b]
Insecticides	5.6 L[b]	319,100[a]
Seeds	16.8 kg[a]	57,000[a]
Total		811,880
Outputs		
Cowpea yield	1,530 kg[a]	5,247,900[a]
kcal output/kcal input		6.46:1

[a] From Doering, O., in *Energy Use Management*, Pergamon Press, New York, 1977, 725–732.

[b] Estimated.

the 2668 kg/ha for soybeans, and the output/input ratio is only 1.8:1 for dry beans. In addition, the protein yield is about half that of soybeans.

COWPEAS

Cowpeas are an important food resource in the United States and many other parts of the world. Cowpea production in north-central Nigeria depends primarily on human power (Doering, 1977). The total energy input is 811,800 kcal/ha, with a labor input of 814 h (419,000 kcal/ha), whereas the yield is 5.2 million kcal/ha (Table 10.19), resulting in an energy output/input ratio of 6.5:1 for this particular cowpea production system.

PEANUTS

Peanuts are an extremely important crop for many people worldwide. In addition to being used for food, they are grown for their valuable oil.

Data on the production of peanuts employing a large input of labor (936 h) for northeast Thailand have been reported by Doering (1977) (Table 10.20). Total inputs, including the large labor input, total 1.9 million kcal/ha, and the peanut yield is 5.0 million kcal/ha. Thus, the output/input ratio for this peanut production system is 2.6:1 (Table 10.20).

Peanut production in the United States (Georgia) yields 15.3 million kcal/ha, or about three times that in Thailand. However, with the large energy expenditure required, the system achieves an output/input ratio of only 1.4:1 (Table 10.21).

AGRICULTURAL TECHNOLOGY

In the future, it will be important to find viable ways to increase yields of grains and legumes while keeping the inputs to a minimum.

TABLE 10.20
Energy Inputs in Northeast Thailand Peanut (Groundnut) Production

	Quantity/ha	kcal/ha
Inputs		
Labor	936 h[a]	585,040
Draft buffalo	0.17 buffalo[a]	1,116,000[a]
Equipment	16,570 kcal[b]	16,570[b]
Insecticides	108,700 kcal[a]	108,700[a]
Nitrogen	2 kg[a]	29,400
Phosphorus	2 kg[a]	6,000
Potassium	2 kg[a]	3,200
Seeds (unshelled)	15 kg[a]	58,500[a]
Total		1,923,410
Outputs		
Peanut yield	1,280 kg[a]	4,992,000[a]
kcal output/kcal input		2.60:1

[a] From Doering, O., in *Energy Use Management*, Pergamon Press, New York, 1977, 725–732.

[b] Estimated.

TABLE 10.21
Energy Inputs in Peanuts (Groundnuts) Produced in Georgia, U.S.A.

	Quantity/ha	kcal/ha
Inputs		
Labor	19 h	8,835
Machinery	20 kg	360,000
Gasoline	63 L	636,867
Diesel	125 L	1,426,750
Electricity	40,997 kcal	40,997
Nitrogen	33 kg	485,100
Phosphorus	69 kg	207,000
Potassium	112 kg	179,200
Lime	1362 kg	408,600
Seeds	127 kg	2,286,000
Insecticides	37 kg	3,215,670
Herbicides	16 kg	1,598,560
Transportation	335 kg	86,095
Total		10,947,674
Outputs		
Peanut yield	3,724 kg	15,305,640
kcal output/kcal input		1.4:1

Source: Pimentel, D. (ed.), *Handbook of Energy Utilization in Agriculture*, CRC Press, Boca Raton, FL, 1980.

Yields can be increased through breeding of high-yielding plant varieties such as IR-8, a rice breed developed at the International Rice Research Institute. Yields can also be augmented by the judicious use of fertilizers and pest control. The Green Revolution was built on the use of fossil energy for fertilizers, pesticides, and irrigation.

New varieties of plants should be resistant to naturally occurring pests that all too often reduce yields and necessitate the use of pesticides. Both fertilizers and pesticides cost in fossil energy and dollars, so anything that can be done to reduce these inputs will be a great benefit. Moreover, all parts of the production system that depend on fossil energy will be constrained as supplies of this nonrenewable resource decrease and prices increase.

In the future, we must also decide whether we can afford to cycle large quantities of grains through our livestock. The production of animal protein costs not only in terms of energy, labor, and land needed to grow the grains but also in terms of the direct cost of the animal husbandry itself. The conversion of grain protein into animal protein is relatively inefficient and therefore expensive to produce by whatever criteria we set.

REFERENCES

AED. 1960. *Cost of Production of Corn*. Manila: Department of Agriculture and National Resources.

Akinwumi, J.A. 1971. Costs and returns in commercial maize production in the derived savanna belt of Western State, Nigeria. *Bulletin of Rural Economists and Sociologists*, Ibadan 6: 219–251.

Allan, P. 1961. Fertilizers and food in Asia and the Far East. *Span* 4: 32–35.

Bureau pour le Development de la Production Agricole (BDPA). 1965. *Techniques Rurales en Afrique. Les temps de traux*. Republiques Française: Ministere de la Cooperation.

De Los Reyes, B.N., E.V. Quintana, R.D. Torres, et al. 1965. A case study of the tractor- and carabao-cultivated lowland rice farms in Laguna, crop year 1962–63. *Philippine Agriculture* 49: 75–94.

Doering, O. 1977. The energy balance of food legume production. In R.A. Fazzolare and C.B. Smith (eds.), *Energy Use Management*, pp. 725–732. New York: Pergamon.

Food and Agriculture Organization (FAO). 1981. *Agriculture: Toward 2000*. Rome: Food and Agriculture Organization of the United Nations.

Freeman, J.D. 1955. *Iban Agriculture*. London: Her Majesty's Stationery Office.

Grant, W.R. and T. Mullins. 1963. Enterprise costs and returns on rice farms in Grant Prairie, Ark. *Arkansas Agricultural Experimental Station Reports Series* 119.

Harrar, J.G. 1961. Socioeconomic factors that limit needed food production and consumption. *Federation Proceedings* 20: 381–383.

Hashimoto, K., A.M. Heagler, and B. McManus. 1992. A comparison of rice production cost, Japan and southwest Louisiana. *Agricultural Economics and Agribusiness* 106.

Heichel, G.H. 1980. Assessing the fossil energy costs of propagating agricultural crops. In D. Pimentel (ed.), *Handbook of Energy Utilization in Agriculture*, pp. 27–33. Boca Raton, FL: CRC Press.

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

Mangelsdorf, P.C. 1966. Genetic potentials for increasing yields of food crops and animals. In *Prospects of the World Food Supply*. Washington, D.C.: Symposium Proceedings of the National Academy of Sciences.

Ministry of Food, Agriculture Community Development and Cooperation (MFACDCGI). 1966. *Farm Management in India*. New Delhi: Directorate of Economy and Statistics, Department of Agriculture, Government of India.

Murugaboopathi, C., M. Tomita, E. Yamaji, et al. 1991. Prospect of large-size paddy field using direct seeding supported by surface irrigation system. *Trans. ASAE* 34(5): 2040–2046.

Pimentel, D. 1974. Energy use in world food production. *Environmental Biology* 74(1).

Pimentel, D. 1976. Crisi energetica e agricoltura. In *Enciclopedia della Scienza e della Tecnica*, pp. 251–266. Milan: Mondadori.

Pimentel, D. (ed.). 1980. *Handbook of Energy Utilization in Agriculture*. Boca Raton, FL: CRC Press.

Pimentel, D. 2006. Impacts of organic farming on the efficiency of energy use in agriculture. An Organic Center State of Science Review. August 2006. http://www.organic-center.org/science.pest.php?action=view&report_id=59.

Pimentel, D. and T. Patzek. 2005. Ethanol production using corn, switchgrass, and wood: Biodiesel production using soybean and sunflower. 2005. *Natural Resources Research* 14(1): 65–76.

Stadelman, R. 1940. Maize cultivation in northwestern Guatemala. In *Contributions to American Anthropology and History, No. 33*. Carnegie Institute of Washington, Washington, D.C., Publication 523, pp. 83–263.

Thurston, H.D. 1969. Tropical agriculture. A key to the world food crises. *BioScience* 19: 29–34.

U.S. Department of Agriculture (USDA). 1974. Fertilizer situation. *Economic Research Service, Report No. FS–4*. Washington, D.C.: U.S. Department of Agriculture.

U.S. Department of Agriculture (USDA). 1975. *Agricultural Statistics 1975*. Washington, D.C.: U.S. Government Printing Office.

U.S. Department of Agriculture (USDA). 1976. *Agricultural Statistics 1976*. Washington, D.C.: U.S. Government Printing Office.

U.S. Department of Agriculture (USDA). 1991. *Agricultural Statistics 1991*. Washington, D.C.: Government Printing Office.

U.S. Department of Agriculture (USDA). 2003. *Agricultural Statistics 2003*. Washington, D.C.: Government Printing Office.

Weaver, S.H. 1980. Energy use in the production of oats. In D. Pimentel (ed.), *Handbook of Energy Utilization in Agriculture*, pp. 85–92. Boca Raton, FL: CRC Press.

11 Energy Use in Fruit, Vegetable, and Forage Production

FRUITS

Fruits, the edible material adhering to the seeds of a plant, are eaten raw, cooked, or dried. Fruits have a high water content, ranging from about 75% to 90%. Carbohydrates, usually in the form of sugar, are the second-largest constituent, ranging from about 6% to 22%. Fruits contain only small amounts of protein and negligible amounts of fats. Citrus fruits, cantaloupes, and strawberries are excellent sources of vitamin C, whereas yellow-orange fruits are considered outstanding sources of beta-carotene, the precursor of vitamin A.

In this section, apple and orange production in the United States are analyzed to illustrate energy expenditure and food energy yield in fruit production.

APPLES

Apples are an economically valuable crop in many parts of the world. In the United States, petroleum products are used to operate machinery employed in apple orchards, and the inputs for this machinery account for a large percentage of the total energy input (Table 11.1). The next largest input is for pesticides, which represent nearly 17% of the total energy input in apple production.

The labor input of 385 h/ha expended in apple production is high compared with those of most other food crops grown in the United States. Most of the labor input occurs during harvesting. The total labor input is calculated to be about 17.1 million kcal/ha, which represents only 34% of the total energy input for apple production. The yield in fruit is about 30.7 million kcal/ha, making the output/input ratio only 0.61:1.

ORANGES

Oranges are another valuable fruit in U.S. agriculture. Although oranges and other citrus fruits have more than double the vitamin C content of potatoes, they supply only about half as much vitamin C in the U.S. diet as potatoes.

The production of oranges requires less energy than apples (Tables 11.1 and 11.2). Specifically, orange production uses less petroleum products and pesticides than apple production. The return in food energy in the form of oranges is 23.5 million kcal/ha, for an output/input ratio of only 1:1. Apples, then, are more energy intensive to produce

TABLE 11.1
Energy Inputs in Apple Production in the Eastern United States

	Quantity/ha	kcal/ha
Inputs		
Labor	385 h	17,150,000
Machinery	88 kg	1,408,000
Diesel	483 L	5,506,000
Gasoline	1346 L	13,406,000
Nitrogen	45 kg	837,000
Phosphorus	114 kg	472,000
Potassium	114 kg	372,000
Insecticides	47 kg	4,700,000
Herbicides	6 kg	600,000
Fungicides	49 kg	4,900,000
Electricity	66 kWh	57,000
Transportation	2974 kg	787,000
Total		50,195,000
Outputs		
Apple yield	55,000 kg	30,660,000
Protein yield	109 kg	
kcal output/kcal input		0.61:1

Source: Pimentel, D., An Organic Center State of Science Review, August 2006, http://www.organic-center.org/science.pest.php?action=view&report_id=59.

TABLE 11.2
Energy Inputs in Orange Production in Florida

	Quantity/ha	kcal/ha
Inputs		
Labor	210 h	9,354,000
Machinery	30 kg	480,000
Diesel	90 L	1,096,000
Gasoline	96 L	960,000
Nitrogen	228 kg	4,239,000
Phosphorus	54 kg	224,000
Potassium	228 kg	783,000
Insecticides	9 kg	900,000
Herbicides	11 kg	1,000,000
Nematicides	37 kg	3,700,000
Electricity	66 kWh	57,000
Transportation	500 kg	128,000
Total		22,921,000
Outputs		
Orange yield	46,000 kg	23,519,000
Protein yield	404 kg	
kcal output/kcal input		1.02:1

Source: Pimentel, D., An Organic Center State of Science Review, August 2006, http://www.organic-center.org/science.pest.php?action=view&report_id=59.

than oranges. From the standpoint of vitamin C content, oranges, with about 50 mg per 100 g, are more valuable than apples, which contain only 3 mg per 100 g.

VEGETABLES

Vegetables are the various parts of herbaceous plants consumed by humans. For example, cabbage and spinach are plant leaves, carrots and turnips are roots, squash and tomatoes are fruits, peas and corn are seeds, onions are bulbs, and potatoes are tubers.

Vegetables are similar to fruits in that they have high water content (80%–95%) and low fat and, except for beans and peas, low protein content. The carbohydrate content, mainly starch, varies considerably from a high of about 22% for lima beans to a low of 2% for lettuce. Vegetables generally have a higher mineral and vitamin content than fruits. In particular, dark green leafy vegetables such as spinach are high in vitamin C, beta-carotene, and iron. Also, except for spinach and chard (goosefoot family), these vegetables are excellent sources of calcium. Oxalic acid in spinach may chemically bind some of the calcium, making it insoluble, hence less available to humans. Many vegetables, especially seeds, are reliable sources of thiamine.

This energy analysis covers a broad cross-section of vegetables, including potatoes, spinach, brussels sprouts, tomatoes, sugar beets, and cassava.

POTATOES

The white potato is one of the 15 most heavily consumed plant foods in the world today. Even in the United States, where a wide variety of vegetables are available, the potato is the most frequently eaten vegetable. There, about 60 kg of potato is consumed per person per year (USDA, 2003).

Based on data from the United States, the greatest energy input in U.S. potato production is fertilizers, which represent about one-quarter of the total inputs (Table 11.3). Another one-quarter of the energy is expended for petroleum and machinery inputs that reduce the human labor input, which averages 35 h/ha. The total energy input for potato production is 17.5 million kcal/ha. The potato yield equals 23.3 million kcal/ha, resulting in an output/input ratio of 1.3:1, slightly lower than the 1.6:1 reported by Leach (1976) for the United Kingdom (Table 11.4). The differences in inputs between U.S. and U.K. production are considered insignificant.

Although potatoes are only 2% protein, the total yield of protein per hectare is substantial, amounting to 814 kg/ha. This is a relatively high yield, especially for a food so high in water content.

SPINACH

Spinach, a green leafy vegetable, is eaten raw or cooked. Although it is not a major vegetable throughout the world, it is nutritionally valuable. Like other dark green leafy vegetables, spinach contributes iron, riboflavin, and vitamins A and C to the diet.

TABLE 11.3
Energy Inputs in Potato Production in the United States

	Quantity/ha	kcal/ha
Inputs		
Labor	35 h	1,964,000
Machinery	31 kg	574,000
Diesel	152 L	1,735,000
Gasoline	272 L	2,750,000
Nitrogen	231 kg	4,294,000
Phosphorus	220 kg	911,000
Potassium	111 kg	362,000
Seeds	2408 kg	1,478,000
Sulfuric acid	64.8 kg	0[a]
Insecticides	3.6 kg	360,000
Herbicides	1.5 kg	150,000
Fungicides	4.5 kg	450,000
Electricity	47 kWh	135,000
Transportation	2779 kg	2,307,000
Total		17,470,000
Outputs		
Potato yield	40,656 kg	23,296,000
Protein yield	722 kg	
kcal output/kcal input		1.33:1

[a] Sulfuric acid production is an exothermic process.

Source: Pimentel, D., An Organic Center State of Science Review, August 2006, http://www.organic-center.org/science.pest.php?action=view&report_id=59.

TABLE 11.4
Energy Inputs in Potato Production in the United Kingdom

	Quantity/ha	GJ/ha[a]
Inputs		
Field work		
Fuel for tractors (to harvest)	2.85 GJ	2.85
Fuel for harvester, transport	3.38 GJ	3.38
Tractor depreciation and repairs	1.14 GJ	1.14
Harvester depreciation and repairs	6.70 GJ	6.70
Nitrogen	175 kg	14.0
Phosphorus	175 kg	2.45
Potassium	250 kg	2.25
Sprays	13 kg	1.24
Seed shed fuels (620 MJ/t seed)	1.57 GJ	1.57
Storage (1.65 kWh/net t)	0.57 GJ	0.57
Total		36.15

TABLE 11.4 (continued)
Energy Inputs in Potato Production in the United Kingdom

	Quantity/ha	GJ/ha[a]
Outputs		
Potato yield	26,300 kg	56.9
Protein yield	376 kg	
Energy output/energy input		1.57:1

[a] 4186 Joule = 1 kcal.

Source: After Leach, G., *Energy and Food Production*, IPC Science and Technology Press Ltd., Guildford, Surrey, UK, 1976.

TABLE 11.5
Energy Inputs in Spinach Production in the United States

	Quantity/ha	kcal/ha
Inputs		
Labor	56 h[a]	26,040[b]
Machinery	30 kg[c]	480,000
Fuel	297 L[a]	2,970,000[a]
Nitrogen	470 kg[a]	6,909,000
Phosphorus	354 kg[a]	1,062,000
Potassium	136 kg[a]	217,600
Limestone	454 kg[a]	143,010
Seeds	33.6 kg[a]	135,300[a]
Irrigation	69,500 kcal[a]	69,500[a]
Insecticides	2 kg[a]	173,820
Herbicides	2 kg[a]	199,820
Electricity	300,000 kcal[a]	300,000[a]
Transportation	287 kg	73,759[d]
Total		12,759,849
Outputs		
Spinach yield	11,200 kg[a]	2,912,000
Protein yield	358 kg	
kcal output/kcal input		0.23:1

[a] Terhune, E., in *Energy Use Management*, Pergamon, New York, 1977, 769–778.

[b] 56 h × 465 kcal/h.

[c] Estimated.

[d] 287 kg × 257 kcal/kg.

The largest energy input in U.S. spinach production is for nitrogen fertilizer, amounting to nearly 50% of the total energy input (Table 11.5). The next largest inputs are for fuel and machinery. The overall energy cost is 12.8 million kcal/ha, and the spinach yield is 2.9 million kcal/ha. The output/input ratio is 0.2:1. This negative ratio means that about 5 kcal of fossil energy is required to produce each kcal of spinach.

TABLE 11.6
Energy Inputs in Tomato Production in the United States

	Quantity/ha	kcal/ha
Inputs		
Labor	363 h	14,580,000
Machinery	100 kg	1,600,000
Diesel	246 L	2,808,000
Gasoline	628 L	6,348,000
Nitrogen	200 kg	3,000,000
Phosphorus	100 kg	300,000
Potassium	150 kg	225,000
Limestone	50 kg	16,000
Seedlings	13,600	100,000
Irrigation	125 cm	1,010,000
Insecticides	1.5 kg	150,000
Herbicides	1.5 kg	150,000
Fungicides	16 kg	1,600,000
Electricity	77.5 kWh	200,000
Transportation	1024 kg	272,000
Total		32,389,000
Outputs		
Tomato yield	41,778 kg	8,358,000
Protein yield	496 kg	
kcal output/kcal input		0.26:1

Source: Pimentel, D., An Organic Center State of Science Review, August 2006, http://www.organic-center.org/science.pest.php?action=view&report_id=59.

TOMATOES

Botanically speaking, tomatoes are fruits, but they are included in this section because they are usually consumed as a vegetable. They are eaten in a variety of ways, including raw, cooked, canned, and as juice. They are valued nutritionally for vitamin C (23 mg per 100 g of raw tomato), vitamin A, and iron.

Based on U.S. data, one-third of the energy inputs in tomato production are for fuel and machinery that reduce labor inputs (Table 11.6). The second largest input is for fertilizers. The total energy input is 32.4 million kcal/ha, and the average tomato yield is 8.4 million kcal/ha. These figures result in an output/input ratio of about 0.26:1, or about 4 kcal of energy expended for every kcal of tomato produced. Because the yield of tomatoes per hectare is so high, the protein yield of 496 kg/ha is excellent, even though tomatoes average only 1% protein and have a high water content.

BRUSSELS SPROUTS

Brussels sprouts are a favorite vegetable in the United Kingdom but are less popular in the United States. Like spinach, they are an excellent source of vitamin A, vitamin C, and iron.

TABLE 11.7
Energy Inputs in Brussels Sprouts Production in the United States

	Quantity/ha	kcal/ha
Inputs		
Labor	60 h[a]	27,900[b]
Machinery	30 kg[c]	480,000
Fuel	285 L[a]	2,881,065
Nitrogen	180 kg[a]	2,646,000
Phosphorus	45 kg[a]	135,000
Potassium	40 kg[a]	64,000
Limestone	40 kg[a]	12,600
Seeds	4 kg[a]	16,120[a]
Insecticides	5 kg[a]	434,550
Herbicides	10 kg[a]	999,100
Electricity	300,000 kcal[c]	300,000[c]
Transportation	249 kg	63,993[d]
Total		8,060,328
Outputs		
Brussels sprouts yield	12,320 kg[a]	5,544,000
Protein yield	604 kg	
kcal output/kcal input		0.69:1

[a] From Pimentel, D., in *Enciclopedia della Scienza e della Tecnica*, Mondadori, Milan, 1976, 251–266.

[b] 60 h × 465 kcal/h.

[c] Estimated.

[d] 249 kg × 257 kcal/kg.

As with most vegetable production, the major energy inputs for Brussels sprout production in the United States are for fuel and machinery, amounting to more than one-third of the total input (Table 11.7). The next major input is for fertilizers. The total energy input for Brussels sprouts production is 8.1 million kcal/ha, and the yield equals about 5.5 million kcal of food energy. Hence, the output/input ratio is 0.7:1. Although Brussels sprouts do not yield as much food energy or protein per hectare as potatoes, they do yield a significant 604 kg/ha of protein. Of the vegetables analyzed here, Brussels sprouts place second to potatoes in calories and protein yield per hectare.

SUGAR BEETS

The sugar beet is another plant that is not generally classed as a vegetable but is included in this section because it is a valuable food commodity in many parts of the world. Both sugar beets and sugarcane contain large quantities of sucrose. Although the sweetener is valued for its energy, it contains no vitamins, minerals, or protein. Sugar beets can be grown in temperate regions, whereas sugarcane can only be produced in tropical or subtropical regions.

TABLE 11.8
Energy Inputs in Sugar Beet Production in the United Kingdom

	Quantity/ha	GJ/ha
Inputs		
Field work		
Tractor fuels (to harvest)	2.50 GJ	2.50
Harvester, transport fuels	2.54 GJ	2.54
Tractor depreciation and repairs	2.00 GJ	2.00
Harvester depreciation and repairs	2.80 GJ	2.80
Nitrogen	160 kg	12.80
Phosphorus	50 kg	0.70
Potassium	150 kg	1.35
Salt	70 kg	0.10
Kainit (17% K_2O)	280 kg	0.43
Sprays	10.9 kg	1.09
Seed (144 MJ/£)	7.5 £	1.08
Total		27.39
Outputs		
Sugar beet yield	35,500 kg	99.1
Energy output/energy input		3.62:1

Note: 4186 Joule = 1 kcal.

Source: After Leach, G., *Energy and Food Production*, IPC Science and Technology Press Ltd., Guildford, Surrey, UK, 1976.

Based on data from Leach (1976), about 50% of the energy input for sugar beet production in the United Kingdom is for nitrogen fertilizer (Table 11.8). Machinery and fuel constitute the second largest input. The beet yield averages 35,500 kg/ha and contains about 16.5% sugar for processing. For sugar alone, the output/input ratio is about 3.6:1, making sugar beets one of the more efficient crops analyzed in this section.

CASSAVA

Cassava is an important crop worldwide, especially in Africa and South America. It is one of the highest producing crops in terms of carbohydrate per hectare but one of the lowest in terms of protein. The low protein content is one of the reasons the crop can grow in soil that is low in nutrients, especially nitrogen.

The data for cassava production are from the Tanga region of Africa. Cassava grown in that region has the efficient output/input ratio of 23:1 (Table 11.9). The root of the cassava shrub is harvested 9–12 months after the planting of stem cuttings. Production of this crop requires about 1300 h of hand labor per hectare. Total energy input is calculated at about 838,300 kcal/ha, and the yield is about 19.2 million kcal/ha. This high energy yield comes mainly from the starch content of cassava.

TABLE 11.9
Energy Inputs in the Tanga Region of Africa for Cassava Production

	Quantity/ha	kcal/ha
Inputs		
Labor	1284 h[a]	821,760[b]
Hoe	16,500 kcal[c]	16,500[c]
Stem cuttings	None	
Total		838,260
Outputs		
Cassava yield	5824 kg	19,219,200
Protein yield	58 kg	
kcal output/kcal input		22.93:1

[a] From Ruthenberg, H., *Smallholder Farming Development in Tanzania*, Munich, Germany, Weltforum Verlag, 1968.

[b] On a per day basis, the human power energy input is 8 h of work at 350 kcal/h; 6 h of other activities at 145 kcal/h; and 10 h of rest at 45 kcal/h. This totals 4120 kcal input per person.

[c] Estimated.

The protein yield, as mentioned, is low, only 58 kg/ha. Furthermore, the quality of cassava protein is considered the lowest of all plant proteins. Given the efficiency of cassava production and the breadth of its consumption in the tropics, it is unfortunate that the quality and quantity of protein is so inadequate.

FORAGE PRODUCTION

Forage production is an essential part of most livestock production systems, especially for ruminant animals. Like all crops, forage requires energy inputs. In general, these crops are not intensively managed because they bring a low monetary return.

Alfalfa, tame hay, and corn silage production are analyzed to estimate typical energy output/input ratios for forage production.

ALFALFA

Alfalfa is not only one of the most productive forages but also one of the most nutritious for livestock. Because it is fairly typical in the United States, data from Ohio were analyzed. The data indicate that the major inputs in U.S. alfalfa production are for fuel and machinery (Table 11.10). Together, these total about 70% of total inputs. In contrast to most other crops, alfalfa needs little or no nitrogen fertilizer; like legumes, it is associated with nitrogen-fixing bacteria. Because nitrogen fertilizer is an energy-costly input, this savings helps keep alfalfa production relatively energy efficient.

The total energy input for alfalfa production is calculated to be 2.5 million kcal/ha. With a yield of about 15.4 million kcal/ha, the output/input ratio is about 6:1.

TABLE 11.10
Energy Inputs in Ohio Alfalfa Production

	Quantity/ha	kcal/ha
Inputs		
Labor	13 h[a]	6,045[b]
Machinery	20 kg[c]	360,000
Gasoline	129 L[a]	1,304,061
Nitrogen	7 kg[a]	103,900
Phosphorus	45 kg[a]	135,000
Potassium	59 kg[a]	94,400
Limestone	179 kg[a]	56,385
Seeds	4.5 kg[a]	279,000[d]
Insecticides	0.4 kg[a]	34,764
Herbicides	0.2 kg[a]	19,982
Electricity	26 kWh[a]	74,438
Transportation	132 kg	33,924[e]
Total		2,501,899
Outputs		
Alfalfa yield	6,832 kg[a]	15,440,320
Protein yield	1,127 kg	
kcal output/kcal input		6.17:1

[a] From U.S. Department of Agriculture (USDA), *Firm Enterprise Data System*. Stillwater, OK, USDA, ERS, and Oklahoma State University Department of Agricultural Economics, 1977.

[b] 13 h × 465 kcal/h.

[c] Estimated.

[d] From Heichel, G.H., in *Handbook of Energy Utilization in Agriculture*, CRC Press, Boca Raton, FL, 1980, 27–33.

[e] 132 kg × 257 kcal/kg.

In addition to a high energy yield, alfalfa provides a high protein yield of about 1100 kg/ha. Alfalfa supplies a major share of the plant protein fed to animals in the United States.

TAME HAY

The major forage feed for cattle, sheep, and other ruminants in the world is tame hay consisting of numerous grass species. Animals are allowed to graze the hay as it grows in the pasture and do the harvesting themselves. Humans mechanically harvest some of the hay, and this production system is analyzed here.

As with alfalfa, two major energy inputs for tame hay production in the United States are for fuel and machinery (Table 11.11). Together these account for about 42% of the total energy expended for production. The average yield is estimated to be about 8.6 million kcal/ha in forage feed energy. Balanced against the total energy input of about 1.7 million kcal/ha, the energy output/input ratio is 5:1 for U.S. tame hay production.

Note that the 5:1 ratio for the United States is far better than the 2:1 ratio reported in the United Kingdom (Table 11.12), even though yield in the United Kingdom are more than double those in the United States. The reason is that the nitrogen input

TABLE 11.11
Energy Inputs in Tame Hay Production in the United States

	Quantity/ha	kcal/ha
Inputs		
Labor	16 h[a]	7,440[b]
Machinery	20 kg[c]	360,000
Fuel	36 L[d]	363,924
Nitrogen	7 kg[d]	102,900
Phosphorus	8 kg[d]	24,000
Potassium	16 kg[d]	25,600
Limestone	15 kg[c]	4,725
Seeds	30 kg[a]	630,000[e]
Herbicides	1 kg[d]	99,910
Electricity	75,000 kcal[c]	75,000[c]
Transportation	88 kg	22,616[f]
Total		1,716,115
Outputs		
Tame hay yield	5,000 kg[a]	8,578,680
Protein yield	200 kg	
kcal output/kcal input		5.0:1

[a] From Pimentel, D., in *Enciclopedia della Scienza e della Tecnica*, Milan, Mondadori, 1976, 251–266.

[b] 16 h × 465 kcal/h.

[c] Estimated.

[d] Federal Energy Administration (FEA), Energy and U.S. Agriculture: 1974 Data Base, Washington, D.C., U.S. Government Printing Office, 1976.

[e] From Heichel, G.H., in *Handbook of Energy Utilization in Agriculture*, CRC Press, Boca Raton, FL, 1980, 27–33.

[f] 88 kg × 257 kcal/kg.

TABLE 11.12
Energy Inputs for Tame Hay Production for a Typical U.K. Production System

	Quantity/ha	GJ/ha[a]
Inputs		
Field work, fuels	2.57 GJ	2.57
Field work, machinery	3.53 GJ	3.53
Nitrogen	250 kg	21.62
Total		27.7
Outputs		
Hay yield	10,300 kg	65.5
Energy output/energy input		2.36:1

[a] 4186 Joule = 1 kcal.

Source: After Leach, G., *Energy and Food Production*, Guildford, Surrey, UK, IPC Science and Technology Press Ltd., 1976.

used in the United Kingdom is more than 30 times that required in the United States. Another, less intensive hay production system in the United Kingdom yielded a more favorable ratio of 6:1 (Table 11.13).

CORN SILAGE

Corn silage consists of mature corn plants that are cut, chopped, and stored in a silo. During storage the chopped corn ferments, and this process helps preserve it. In U.S. production, the total energy input for silage production averages 6.3 million kcal/ha (Table 11.14). Even with 70% water content, corn silage produces high yields,

TABLE 11.13
Energy Inputs in Tame Hay Production in an Efficient U.K. Production System

	Quantity/ha	GJ/ha[a]
Inputs		
Field work, machinery	2.0 GJ	2.0
Nitrogen	80 kg	7.48
Total		9.48
Outputs		
Hay yield	5600 kg	53.0
Energy output/energy input		5.6:1

[a] 4186 Joule = 1 kcal

Source: After Leach, G., *Energy and Food Production*, Guildford, Surrey, UK, IPC Science and Technology Press Ltd., 1976.

TABLE 11.14
Energy Inputs in New York Corn Silage Production

	Quantity/ha	kcal/ha
Inputs		
Labor	15 h[a]	6,975[b]
Machinery	40 kg[c]	720,000
Diesel	110 L[d]	1,255,540
Gasoline	105 L[d]	1,071,554
Nitrogen	116 kg[a]	1,705,200
Phosphorus	66 kg[a]	198,000
Potassium	75 kg[a]	120,000
Limestone	560 kg[a]	176,400
Seeds	19 kg[a]	475,000[e]
Insecticides	2.5 kg[a]	217,275
Herbicides	2.5 kg[a]	249,775
Electricity	12 kWh[d]	34,356
Transportation	211 kg	54,227[f]
Total		6,284,302

TABLE 11.14 (continued)
Energy Inputs in New York Corn Silage Production

	Quantity/ha	kcal/ha
Outputs		
Corn silage yield	31,020 kg[a]	25,284,402
Protein yield	393 kg	
kcal output/kcal input		4.02:1

[a] From Snyder, D.P., *Agricultural Economic Research Report* 25, Cornell University Agricultural Experiment Station, Ithaca, NY, 1976.

[b] 15 h × 465 kcal/h.

[c] Estimated.

[d] Federal Energy Administration (FEA), Energy and U.S. Agriculture: 1974 Data Base, U.S. Government Printing Office, Washington, D.C., 1976.

[e] From Heichel, G.H., in *Handbook of Energy Utilization in Agriculture*, CRC Press, Boca Raton, FL, 1980, 27–33.

[f] 211 kg × 257 kcal/kg.

averaging 25.3 million kcal/ha. Thus, the output/input ratio for corn silage is 4:1, significantly greater than the 2.5:1 output/input ratio for corn grain.

VEGETARIANISM AND NONVEGETARIANISM AND ENERGY INPUTS

In Chapters 8 through 11, energy inputs for the production of various animal and plant foods have been analyzed. The question then arises as to what the fossil fuel requirements would be for human diets made up of various combinations of animal and plant foods. Do some diets use more fossil energy than others? Humans seldom eat just one or two foods; rather, they make dietary choices from a variety of available foods. Basically, however, eating patterns can be classified as to the type of protein eaten. Nonvegetarian diets include both animal and plant proteins, often, as in the United States, with a predomination of animal protein. In the lacto-ovo diet, eggs, milk, and milk products represent the only animal protein eaten, whereas in the complete vegetarian diet no animal protein is eaten.

The following analysis illustrates some of the differences in the fossil fuel requirements of these three dietary regimes. The calculations are based on data for various foods produced in the United States. The average daily food intake in the United States is 3500 kcal (Pimentel and Pimentel, 2003), so we assumed a constant intake of 3500 kcal/day for all three types of diets. The protein intake is over 100 g per day in the nonvegetarian diet and declines to about 80 g in the all-vegetarian diet. Both protein intakes significantly exceed the recommended daily allowance of 56 g/day.

Nearly twice as much fossil energy is expended for the food in a nonvegetarian diet as in the vegetarian diet (Figure 11.1). As expected, the lacto-ovo diet is more energy intensive than the all-vegetarian diet. Based on these sample calculations, the pure vegetarian diet is more economical in terms of fossil energy than either of the other two types of diets.

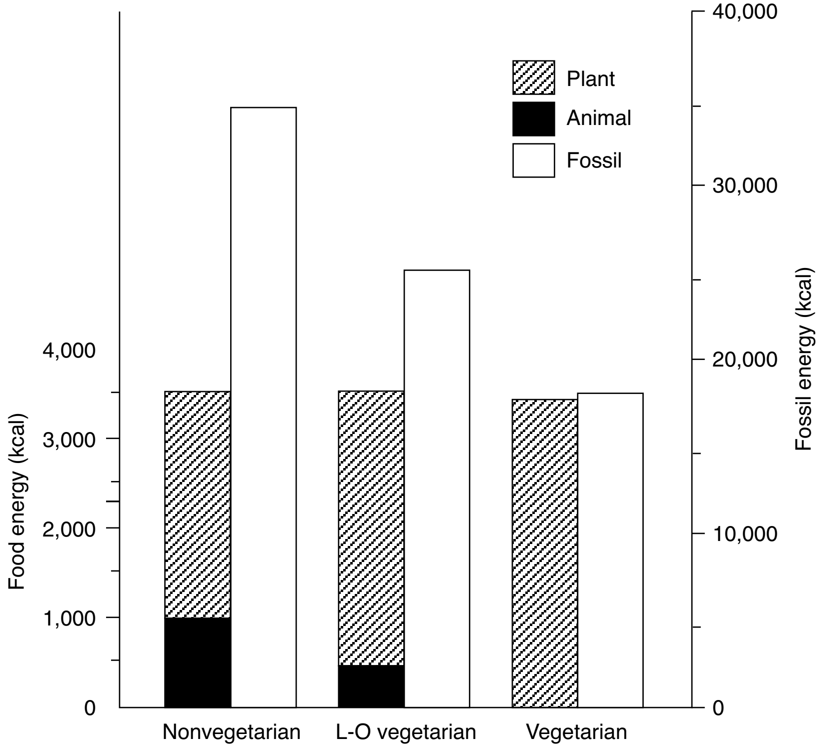

FIGURE 11.1 Daily food energy intake of pure vegetarians, lacto-ovo (L-O) vegetarians, and nonvegetarians and the calculated fossil energy inputs to produce these diets under U.S. conditions.

Energy expenditure is not the only factor to be evaluated when dietary choices are made. Decisions are often based on individual preferences and tastes. In addition, there are significant nutritional differences between the pure vegetarian diet and those that include animal products. Pure vegetarian diets lack vitamin B_{12}, an essential nutrient, so this must be taken as a dietary supplement. Further, the quality of protein depends on the combination of foods consumed. When the essential amino acids from a variety of plant food are combined, then the protein quality of a vegetarian diet will be satisfactory. A pure vegetarian diet usually consists of greater volume and bulk than a mixed diet, making it difficult for young children to consume the quantities necessary to meet all nutritional needs. In addition, nutritionally vulnerable people such as infants, rapidly growing adolescents, and pregnant and lactating women may need nutritional supplements of vitamins A and D, calcium, and iron while on a pure vegetarian diet.

When faced with future food options, both in agricultural policy and in personal diet, we must consider the fact that plant food is significantly more energy efficient to produce than a combination of animal and plant food.

REFERENCES

Federal Energy Administration (FEA). 1976. *Energy and U.S. Agriculture: 1974 Data Base.* Washington, D.C.: U.S. Government Printing Office.

Heichel, G.H. 1980. Assessing the fossil energy costs of propagating agricultural crops. In D. Pimentel (ed.), *Handbook of Energy Utilization in Agriculture*, pp. 27–33. Boca Raton, FL: CRC Press.

Leach, G. 1976. *Energy and Food Production*. Guildford, Surrey, UK: IPC Science and Technology Press Ltd.

Pimentel, D. 1976. Crisi energetica e agricoltura. In *Enciclopedia della Scienza e della Tecnica*, pp. 251–266. Milan: Mondadori.

Pimentel, D. 2006. Impacts of organic farming on the efficiency of energy use in agriculture. An Organic Center State of Science Review. August 2006. http://www.organic-center.org/science.pest.php?action=view&report_id=59.

Pimentel, D. and M. Pimentel. 2003. Sustainability of meat-based and plant-based diets and the environment. *Am J Clin Nutr* 78 (suppl.): 660S–663S.

Ruthenberg, H. 1968. *Smallholder Farming Development in Tanzania*. Munich, Germany: Weltforum Verlag Munich.

Snyder, D.P. 1976. Field crops costs and returns from farm cost accounts. *Agricultural Economic Research Report* 25 (1976). Ithaca, NY: Cornell University Agricultural Experiment Station.

Terhune, E. 1977. Energy use in crop production: Vegetables. In R.A. Fazzolare and C.B. Smith (eds.), *Energy Use Management*, pp. 769–778. New York: Pergamon.

U.S. Department of Agriculture (USDA). 1977. *Firm Enterprise Data System*. Stillwater, OK: USDA, ERS, and Oklahoma State University Department of Agricultural Economics.

U.S. Department of Agriculture (USDA). 2003. *Agricultural Statistics 2003.* Washington, D.C.: Government Printing Office.

12 Energy Inputs in Crop Production in Developing and Developed Countries*

David Pimentel, Rachel Doughty, Courtney Carothers, Sonja Lamberson, Nirali Bora, and Katherine Lee

The energy and economic aspects of 20 cropping systems in developing and developed countries were analyzed. In developing countries, labor input was a major cost in terms of energy and economics while, as in developed countries, the major costs were mechanization and fertilizers. The energy inputs per hectare in developing countries ranged from 7732 MJ (wheat) to 54,647 MJ (cassava); in the United States (developed), the energy inputs ranged from 10,085 MJ (soybean) to 210,817 MJ (apple). Food calories produced per hectare in developing countries ranged from only 12,403 MJ (tomato) to 196,510 MJ (cassava); in the United States, production ranged from 37,947 MJ (wheat) to 128,755 MJ (apple). Grain yields per hectare increased as much as fourfold during the Green Revolution but most of this increase was due to fossil energy inputs including fertilizers, irrigation, and pesticides. Despite the Green Revolution and genetic engineering technologies, per capita grain yields during nearly two decades have been declining—a distressing trend with more than 3 billion people malnourished worldwide.

INTRODUCTION

FOOD AND POPULATION

Adequate supplies of staple food crops are needed by people who rely on these foods for their health and very survival, this is especially importance as the human population increases and the resources that support crop production diminish. The staple crops include wheat, rice, corn soybeans, white potato, sweet potato, cassava, and others (Pimentel and Pimentel, 1996). Consider that worldwide more than 3 billion

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people are currently malnourished (WHO, 1996). This is the largest number and percentage of malnourished humans ever recorded in history. The United Nations University (1999) projects that Africa will be able to feed only 40% of its population in 2025. Recent reports from the Food and Agriculture Organization of the United Nations and the U.S. Department of Agriculture, as well as from numerous other international organizations, further confirm the serious nature of the global food shortages (Population Summit of the World's Scientific Academies, 1994).

The world human population is currently at more than 6 billion and based on current rates of increase, it is projected to double to approximately 12 billion in less than 50 years (PRB, 2000). Thus, great pressure is being placed on all the resources essential for food production, and especially fossil energy, which is a finite resource.

Through continued use, cropland is degraded, water is polluted, fossil energy supplies diminished, and biological resources lost; and all these resources are vital to human survival. These losses further restrict present agricultural production and its expansion to meet additional food needs (Pimentel et al., 1999). Although increases in crop yields have been achieved in fossil-fuel dependent agriculture, intensive use of cropland production is causing widespread soil erosion (Pimentel and Pimentel, 1996).

WORLD ENERGY RESOURCES

Humans rely on various sources of power for food production, housing, clean water, and a productive environment. These range from human, animal, wind, tidal, and water energy to wood, coal, gas, oil, and nuclear sources. Of these, fossil fuel resources have been most effective in increasing food production and feeding a growing number of humans, and help alleviate malnourishment and numerous other diseases (Pimentel and Pimentel, 1996).

About 445 quads (1 quad = 10^{15} BTU; 445 quads = 111×10^{15} kcal or 384×10^{18} J) of fossil and renewable energy sources are used worldwide each year for all human needs (DOE/EIA, 1996; British Petroleum Statistical Review of World Energy, 1999). In addition, about 50% of all the solar energy captured by photosynthesis and incorporated in biomass worldwide is used by humans. Although this amount of biomass energy is very large (approximately 600 quads), it is inadequate to meet the food needs of all humans (Pimentel et al., 1999). To compensate, about 384 quads of fossil energy (oil, gas, and coal) are utilized each year worldwide (DOE/EIA, 1996; British Petroleum Statistical Review of World Energy, 1999). Of this amount, 91 quads are utilized in the United States (about 17% in the food system) (USBC, 1998). Yearly, the U.S. population consumes about 53% more fossil energy than all the solar energy captured by harvested U.S. crops, forest products, and all other vegetation.

The current high rate of energy expenditure throughout the world is directly related to many factors, including rapid population growth, urbanization, and high resource-consumption rates. Indeed, fossil energy use has been increasing at a rate even faster than the rate of growth of the world population. Energy use has been doubling every 30 years whereas world population has been doubling every 40 years (PRB, 2000; DOE/EIA, 1996). Future energy use is projected to double every 32 years while the population is projected to double in about 50 years (PRB, 2000; DOE/EIA, 1996).

Some developing nations with high population growth rates are increasing fossil fuel use in their agricultural production to meet the increasing demand for food and fiber. For instance, in China between 1955 and 1992, fossil energy use in agriculture for irrigation and for producing fertilizers and pesticides increased 100-fold (Wen and Pimentel, 1992).

The overall projections of the availability of fossil energy resources for mechanization, fertilizers, and pesticides are discouraging because the availability of fossil fuels is finite. The world supply of oil is projected to last 40 to 50 years (Campbell, 1997; Youngquist, 1997; Ivanhoe, 2000; Duncan, 2001). The natural gas supply is adequate for about 50 years and coal for about 100 years (British Petroleum Statistical Review of World Energy, 1999; Youngquist, 1997; Bartlett and Ristinen, 1995). These estimates are based on current consumption rates and current population numbers.

Youngquist (1997) reports that current oil and gas exploration drilling data have not borne out some of the earlier optimistic estimates of the amount of these resources yet to be found in the United States. Both the production rate and proven reserves continue to decline. Oil and gas are imported in ever increasing amounts each year (British Petroleum Statistical Review of World Energy, 1999; Youngquist, 1997; DOE, 1991), indicating that neither is now sufficient for U.S. domestic needs and supplies. Analyses suggest that by 1998 the United States had already consumed about three-quarters of its recoverable oil and that the last 25% was in the process of being consumed (Ivanhoe, 2000).

To help alleviate the diminishing fossil energy supplies, available renewable energy technologies, such as biomass and wind power, could provide an estimated 200 quads of renewable energy worldwide (Pimentel et al., 1999; Yao, X., 1998, personal communication). Note that 200 quads is only about half of the energy currently consumed. However, producing 200 quads of renewable energy will require transferring some agricultural land, like pastures, to energy production.

METHODOLOGY

The energy expenditures and economic costs of major food crop production systems both in developed and developing countries are analyzed, including some systems dependent on human labor and draft animal power. For data on developed countries, information on food crop production in the United States was used because abundant data were available and they are similar to intensive crop production systems in other developed nations. For example, in the United States the average energy input for wheat production is about 17.8 GJ, in Germany the average is reported to be 17.5 GJ, and in Greece the input is 21.1 GJ (Tsatsarelis, 1993; Kuesters and Lammel, 1999). Accounting procedures used in the United States, Germany, and Greece differed somewhat because of the availability of data. In addition, a wide range of technology is used in wheat production in all countries, ranging from low input organic to high input irrigated production. The data detailed for the U.S. system are presented.

In developed countries, most of the energy inputs are fossil energy inputs for mechanization and fertilizers whereas in developing countries the major energy expenditure is for human labor. For instance, in U.S. grain production, the labor input was approximately 10 h/ha while in many developing countries the labor input was approximately 1000 h/ha. Labor is a vital component of crop production and also is substituted for mechanization and other farming activities. More than nine different procedures are used for measuring the cost of labor input in terms of energy (Giampietro and Pimentel, 1990; Fluck, 1992). In this study, 2000 h of labor input per year per person is assumed or 8 h per day for 250 days. This is an average figure for the United States but varies throughout the world (USBC, 1998). The energy input for labor was based on the number of hours of labor per hectare and the average consumption of fossil energy (about 8100 L of oil equivalents) per person per year in the United States (British Petroleum Statistical Review of World Energy, 1999). The fossil energy consumption per person in each country varies. In contrast in India, the average is only 280 L per person per year (British Petroleum Statistical Review of World Energy, 1999). Large labor inputs in crop production are less costly in India than in the United States.

In addition to labor, assigning an energy value to manure is difficult. Properly applied manure can be substituted for commercial nitrogen, phosphorus, and potassium fertilizers produced using high inputs of fossil energy. But because different types of manure are used, are handled differently, and are applied in various ways, the values obtained by investigators are highly variable. For example, the nitrogen content of manure varies from 3% to 20% (dry weight) depending on the type of livestock manure used and how it was handled.

Energy inputs for farm machinery, ranging from a hoe to tractor, are difficult to assess. In the United States for example, farm machinery assets per crop hectare total about $538, and last about 10 years, with yearly repairs, estimated to add about 25% per year (USDA, 2000). Knowing the weight of the farm machinery used per hectare per year, Doering (1980) provides detailed data on the energy input required for U.S. production. In this analysis, values were based on the data in the published literature (Doering, 1980).

Fossil fuels differ in their relative importance in agriculture, with liquid fuels used more extensively than natural gas and coal. However, no attempt was made to rate and identify the amount of liquid fuel (oil) used in each cropping system. For nine of the crops in both developed and developing countries, a detailed accounting of the inputs is listed and for eleven additional crops a summary is given of the energy and economic costs.

For economic accounting, data from each particular country were used. The economies of all developed and developing countries differ significantly from one another and these differences should be considered when examining the reported economic data.

ENERGY INPUTS AND ECONOMIC COSTS FOR MAJOR CROPS

The crop systems selected for this analysis were rice, corn, wheat, soybeans, cassava, potato, sweet potato, and cabbage, and they provide most of the world's food supply. In addition, apples, oranges, and tomatoes were included as examples of crops that provide limited calories but excellent minerals and vitamins.

CORN

Corn is one of the world's major grain crops (FAO, 1997). Under favorable environmental conditions, it is one of the most productive crops per unit area of land. An analysis of energy inputs and yields suggests that the high yields of intensive corn production are in part related to the large inputs of fertilizers, irrigation, and pesticides.

Nevertheless, by investing many hours of labor a farmer in a developing country can produce 1200 kg/ha of corn (Table 12.1). For example, corn production by hand in Indonesia requires about 634 h of labor and 5 h of bullock power per hectare, causing an energy expenditure of 17.0 GJ. With a corn yield of 1200 kg/ha in Indonesia (18.1 GJ), the energy input/output ratio is 1:1.07 (Table 12.1). Note that the energy input is slightly higher than it might be if the energy for the bullock power were withdrawn. The bullocks mostly consume forage so little or no fossil energy is expended for them.

The energetics of intensive U.S. corn production are distinctly different from those of the labor-intensive corn production of Indonesia. The total input of human labor is only 11.4 h per hectare compared with 634 h in the labor-intensive system of Indonesia (Tables 12.1 and 12.2).

TABLE 12.1
Energy Inputs and Costs of Corn Production per Hectare in Indonesia

Inputs	Quantity	MJ	Costs ($)
Labor	634 h[a]	5,389[b]	37.00[a]
Bullock (pair)	5 h[a]	46[c]	5.00[d]
Machinery	10 kg[d]	714[e]	1.00[d]
Nitrogen	71 kg[f]	5,544[g]	8.70[a]
Phosphorus	36 kg[f]	622[g]	2.00[a]
Manure	580 kg[a]	4,040[c]	5.00[a]
Pesticides	0.4 L	168[e]	0.70[a]
Seeds	33.6 kg[f]	508[e]	4.60[d]
Total		17,031	64.00
Corn yield = 1200 kg[a]		18,144[e]	
		kcal input/output = 1:1.07	

[a] Djauhari et al. (1988).

[b] Per capita use of fossil energy in Indonesia is about 405 L of oil equivalents per year (British Petroleum, 1999).

[c] Tripathi and Sah (2001).

[d] Estimated.

[e] Pimentel (1980).

[f] Doughty (2000).

[g] FAO (1999).

TABLE 12.2
Energy Inputs and Costs of Corn Production per Hectare in the United States

Inputs	Quantity	kcal × 1000	Costs ($)
Labor	11.4 h[a]	462[b]	114.00[c]
Machinery	55 kg[d]	1,018[e]	103.21[f]
Diesel	42.2 L[g]	481[e]	8.87[h]
Gasoline	32.4 L[g]	328[e]	9.40[h]
Nitrogen	144.6 kg[i]	2,688[j]	89.65[h]
Phosphorus	62.8 kg[i]	260[j]	34.54[h]
Potassium	54.9 kg[i]	179[j]	17.02[h]
Lime	699 kg[i]	220[e]	139.80[k]
Seeds	21 kg[a]	520[e]	74.81[l]
Irrigation	33.7 cm[m]	320[e]	123.00[n]
Herbicides	3.2 kg[o]	320[e]	64.00[p]
Insecticides	0.92 kg[o]	92[e]	18.40[p]
Electricity	13.2 kWh[g]	34[e]	2.38[q]
Transportation	151 kg[r]	125[e]	45.30[s]
Total		7,047	844.38
7,965 kg yield[l]		28,674	

kcal input/output = 1:4.07

[a] National Agricultural Statistics Service (1999).

[b] It is assumed that a person works 2000 h/year and utilizes an average of 8100 L of oil equivalents per year.

[c] It is assumed that farm labor is paid $10 per hour.

[d] Pimentel and Pimentel (1996).

[e] Pimentel (1980).

[f] Hoffman et al. (1994).

[g] USDA (1991).

[h] Hinman et al. (1992).

[i] USDA (1997a,b).

[j] FAO (1999).

[k] USDA (1999b).

[l] USDA (1998).

[m] McGuckin et al. (1992).

[n] Cost of irrigation.

[o] National Agricultural Statistics Service (1997).

[p] It is assumed that herbicide and insecticide prices are $20 per kg.

[q] Price of electricity is 7¢ per kWh (USBC, 1998).

[r] Goods transported include machinery, fuels, and seeds that were shipped an estimated 1000 km.

[s] Transport was estimated to cost 30¢ per kg.

The fossil energy inputs in U.S. corn production, primarily oil for machinery and natural gas for nitrogen fertilizers, are high. Nitrogen fertilizer represents the largest single input, about 40% of the total fossil energy inputs while 25% is expended for labor reducing mechanization (Table 12.2). The total fossil fuel input is estimated to be 29.6 GJ/ha (Table 12.2). The corn yield is also high, about 8000 kg/ha, or the equivalent of 120.4 GJ/ha of food energy, resulting in an input/output ratio of 1:4.07.

While corn yields are higher in the intensive system than the labor-intensive system, the economic investment is also high or $844/ha compared with $62.50/ha for the labor-intensive system (Tables 12.1 and 12.2).

WHEAT

Wheat and rice are the two most important cereal crops grown in the world today; humans eat more wheat than any other cereal grain. Wheat is produced employing diverse techniques with energy sources ranging from human labor and animal power to mechanization. As with corn production, energy inputs and yields vary with each wheat production system.

For example, wheat farmers in Kenya use human and bullock power (Table 12.3). The total energy input in this system is about 7.7 GJ that provides a harvest of about 25.4 GJ in wheat (Table 12.3), for an energy input/output ratio of about 1:3.29. Similar to corn production using bullocks, this energy ratio would be higher if the energy for the bullocks were removed from the assessment.

Wheat production in the United States requires 17.8 GJ of fossil energy inputs compared with 7.7 GJ for the low input Kenyan production system (Tables 12.3 and 12.4). Large machinery powered by fossil fuels replaces the animal power and dramatically reduces the labor input from 684 h for Kenya to only 7.8 h for the U.S.

TABLE 12.3
Energy Inputs and Costs of Wheat Production per Hectare in Kenya

Inputs	Quantity	MJ	Costs ($)
Labor	684 h[a,b]	710[c]	15.39[b]
Machinery	10 kg[d]	672[e]	56.19[b]
Diesel	35 L[d]	1,617[e]	7.35[b]
Nitrogen	22 kg[f]	1,327[g]	12.51[a]
Phosphorus	58 kg[a]	647[g]	32.99[a]
Seeds	202 kg[a]	2,545[e]	61.08[a]
Transportation	200 kg[a]	214[e]	15.84[a]
Total		7,732	201.38
Wheat yield = 1,788 kg[b]		25,414	
		kcal input/output = 1:3.29	

[a] Hassan et al. (1993).

[b] Longmire and Lugogo (1989).

[c] Per capita use of fossil energy in Kenya is estimated to be 522 L of oil equivalents per year based on African data (British Petroleum, 1999).

[d] Estimated.

[e] Pimentel (1980).

[f] Arama (1994).

[g] Surendra et al. (1989).

TABLE 12.4
Energy Inputs and Costs of Winter Wheat Production per Hectare in the United States

Inputs	Quantity	MJ	Costs ($)
Labor	7.8 h	1,327[a]	78.00[b]
Machinery	50 kg[c]	3,360[d]	182.00[e]
Diesel	49.5 L[f]	2,373[d]	10.40[e]
Gasoline	34.8 L[f]	1,478[d]	9.98[e]
Nitrogen	68.4 kg[g]	5,342[h]	41.93[e]
Phosphorus	33.7 kg[g]	588[h]	18.53[e]
Potassium	2.1 kg[g]	29[h]	0.65[e]
Seeds	60 kg[b]	916[d]	16.77[e]
Herbicides	4 kg[b]	1,680[d]	11.83[b]
Insecticides	0.05 kg[g]	21[d]	0.80[i]
Fungicides	0.004 kg[g]	2[d]	0.20[i]
Electricity	14.3 kWh[d]	172[d]	1.00[j]
Transportation	197.9 kg[k]	517[d]	59.37[k]
Total		17,805	431.46
Winter wheat yield	2670 kg[l]	37,947[d]	
		kcal input/output = 1:2.13	

[a] It is assumed that a person works 2000 h per year and utilizes an average of 8100 L of oil equivalents per year.

[b] Willet and Gary (1997).

[c] Estimated.

[d] Pimentel (1980).

[e] Hinman et al. (1992).

[f] Pimentel and Pimentel (1996).

[g] USDA (1997a,b).

[h] FAO (1999).

[i] It is assumed that insecticides and fungicides cost an average of $40 per kg, or same as herbicides.

[j] Price of electricity is 7¢ per kWh (USBC, 1998).

[k] The goods transported include machinery, fuels, and seeds and it is assumed that they were transported an average distance of 1000 km that cost about 30¢ per kg. For energy inputs see Pimentel (1980).

[l] USDA (1998).

system (Tables 12.3 and 12.4). The heavy use of fertilizers and other inputs increased wheat yields from approximately 1788 kg/ha to 2670 kg/ha (Table 12.4). Yet, the input/output ratio is lower than that of Kenya or approximately 1:2.13.

RICE

Rice is the staple food for an estimated 3 billion people, most of whom live primarily in developing countries. This heavy consumption makes an analysis of various rice production technologies particularly relevant.

TABLE 12.5

Energy Inputs and Costs of Draft Animal-Produced Rice per Hectare in the Valley of Garhwal Himalaya, India

Inputs	Quantity	MJ	Costs ($)
Labor	1,703 h[a]	9,996[b]	129.86[a]
Bullocks	328 h[a]	1,499[a]	40.00[a]
Machinery	2.5 kg[c]	172[d]	11.00[c]
Nitrogen	12.3 kg[a]	962[e]	1.30[f]
Phosphorus	2.5 kg[a]	42[e]	0.30[f]
Manure	3,056 kg[a]	21,298[a]	14.91[a]
Seeds	44 kg[a]	672[a]	6.44[a]
Pesticides	0.3 kg[a]	126[e]	1.33[a]
Total		34,767	194.14
Rice yield = 1831 kg[a]		27,917[c]	
		kcal input/output = 1:0.80	

[a] Tripathi and Sah (2001).

[b] Per capita fossil energy use in India is 280 L of oil equivalents per year (British Petroleum, 1999).

[c] Estimated.

[d] Pimentel (1980).

[e] FAO (1999).

[f] The total for fertilizers reported in Tripathi and Sah (2001) was $1.60; we allocated $1.30 for nitrogen.

The rice production system practiced by Indian farmers using human labor and bullocks requires 1703 h of human labor and 328 h of bullock labor per hectare, which totals about 1.5 GJ (Table 12.5). The total rice yield is 1831 kg/ha (34.8 GJ), which results in an energy input/output ratio of about 1:0.80 (Table 12.5).

As in the production of other grains, the United States uses large inputs of fossil energy to produce rice (Table 12.6). Although most of the energy expended is used for machinery and fuel to replace labor, fertilizers account for about half of the total fossil energy input. The human labor input of only 24 h/ha is much lower than in India, but is 6.720 kg/ha (102.4 GJ of food energy). The fossil energy investment is about 49.7 GJ, resulting in an energy input/output ratio of 1:2.06 (Table 12.6).

SOYBEANS

Because of its high protein content (about 34%), the soybean is probably the single most important protein crop in the world. Two-thirds of all soybeans produced are grown in the United States, China, and Brazil. In the United States, relatively little of the soybean crop is used as human food, but is instead processed for its oil while the seed cake and soybean meal are fed to livestock. Soybeans and soy products head the list of U.S. agricultural exports (USDA, 1998).

TABLE 12.6
Energy Inputs and Costs of Rice Production per Hectare in the United States

Inputs	Quantity	MJ	Costs ($)
Labor	24 h[a]	4,082[b]	240.00[c]
Machinery	38 kg[a]	3,116[d]	150.00[e]
Diesel	225 L[a]	10,807[d]	47.25[f]
Gasoline	55 L[a]	2,344[d]	15.95[f]
Nitrogen	150 kg[g]	11,714[h]	93.00[f]
Phosphorus	49 kg[g]	853[d]	26.95[f]
Potassium	56 kg[g]	769[h]	17.36[f]
Sulfur	20 kg[g]	126[i]	1.00[i]
Seeds	180 kg[a]	3,032[d]	90.00[j]
Herbicides	7 kg[g]	2,940[d]	280.00[k]
Insecticides	0.1 kg[g]	42[d]	4.00[l]
Fungicides	0.16 kg[g]	67[d]	6.40[l]
Irrigation	250 cm[a]	8,984[a]	294.00[m]
Electricity	33 kWh[a]	357[a]	2.31[n]
Transportation	451 kg[a]	487[a]	135.30[o]
Total		49,720	1403.52
Rice yield = 6720 kg[p]		102,451	
		kcal input/output = 1:2.06	

[a] Pimentel and Pimentel (1996).

[b] It is assumed that a person works 2000 h per year and utilizes an average of 8100 L of oil equivalents per year.

[c] We assume that a farm laborer earns $10 per hour.

[d] Pimentel (1980).

[e] Estimated.

[f] Hinman et al. (1992).

[g] USDA (1997a,b).

[h] FAO (1999).

[i] Based on the estimate that sulfur costs 5¢ per kg (Myer, 1977) it was calculated that the fossil energy input to produce 1 kg was 1500 kcal.

[j] Seeds were estimated to cost 50¢ per kg.

[k] Hinman and Schiriman (1997).

[l] Insecticides and fungicides were estimated to cost $40 per kg.

[m] 1 cm of irrigation water applied was estimated to cost $1.18.

[n] Price of electricity is 7¢ per kWh (USBC, 1998).

[o] Transportation was estimated to be 30¢ per kg transported 1000 km.

[p] USBC (1998).

In Illinois, typical of soybean cultivation, soybean yields an average 3000 kg/ha and provides about 50.8 GJ (Table 12.7). Production inputs mainly for machinery total 10.1 GJ/ha, an input/output ratio of 1:5.04.

Like other legumes soybeans need less nitrogen than other crops because under most conditions soybeans and other legumes biologically fix their own nitrogen.

TABLE 12.7
Energy Inputs and Costs of Soybean Production per Hectare in Illinois

Inputs	Quantity	MJ	Costs ($)
Labor	7.1 h	1210[a]	71.00[b]
Machinery	20 kg	1512[c]	148.00[d]
Diesel	38.8 L[e]	1856[c]	8.15[f]
Gasoline	25.7 L[e]	1092[c]	7.45[f]
LP gas	3.3 L[e]	105[c]	0.66[f]
Nitrogen	3.7 kg[g]	290[h]	2.29[f]
Phosphorus	37.8 kg[g]	655[h]	38.35[f]
Potassium	14.8 kg[g]	202[h]	4.59[f]
Seeds	69.3 kg[e]	2327[c]	48.58[i]
Herbicides	1.3 kg[g]	546[c]	26.00[j]
Electricity	10 kWh[k]	122[c]	0.70[l]
Transportation	154 kg[m]	168[c]	46.20[n]
Total		10,085	401.97
Potato yield = 3000 kg[i]		50,778	
		kcal output/input = 5.04	

[a] It is assumed that a person works 2000 h per year and utilizes an average of 8100 L of oil equivalents per year.

[b] It is assumed that a farm laborer earns $10 per hour.

[c] Pimentel (1980).

[d] College of Agricultural, Consumer and Environmental Sciences (1997).

[e] Ali and McBride (1999).

[f] Hinman et al. (1992).

[g] Economic Research Statistics (1997).

[h] FAO (1999).

[i] United Soybean Board (1999).

[j] It is assumed that the price of herbicides is $20 per kg.

[k] Pimentel and Pimentel (1996).

[l] Price of electricity is 7¢ per kWh (USBC, 1998).

[m] The goods transported include machinery, fuels, and seeds.

[n] Transport of goods was assumed to cost 30¢ per kg.

The biological nitrogen fixation process carried out by soil microbes uses about 5% of the sunlight energy captured by the soybean plants, but saves the energy that otherwise would be required for nitrogen fertilizer production.

POTATOES

The white potato is one of the 15 most heavily consumed plant foods in the world today. Even in the United States, where a wide variety of vegetables is available, more potatoes are eaten than any other vegetable, about 22 kg of potato per person per year (USDA, 1998). Potatoes contain some protein (1.5–2.5%), are high in vitamin C and potassium, and are a substantial source of carbohydrates.

TABLE 12.8
Energy Inputs and Costs of Potato Production per Hectare in the United States

Inputs	Quantity	MJ	Costs ($)
Labor	35 h[a]	6,720[b]	350.00[c]
Machinery	31 kg[a]	2,411[d]	300.00[e]
Diesel	152 L[a]	7,287[d]	31.92[e]
Gasoline	272 L[a]	11,550[d]	78.88[e]
Nitrogen	231 kg[f]	18,035[g]	142.60[e]
Phosphorus	220 kg[f]	3,826[g]	121.00[e]
Potassium	111 kg[f]	1,520[g]	34.41[e]
Seeds	2,408 kg[d]	6,208[d]	687.00[e]
Sulfuric acid	64.8 kg[a]	0[h]	73.00[i]
Herbicides	1.5 kg[j]	630[d]	13.50[e]
Insecticides	3.6 kg[j]	1,512[d]	14.40[e]
Fungicides	4.5 kg[j]	1,890[d]	180.00[e]
Electricity	47 kWh[a]	567[d]	3.29[k]
Transportation	2,779 kg[l]	9,689[d]	833.70[i]
Total		71,845	2810.90
Potato yield = 38,820 kg[j]		93,425	
		kcal input/output = 1:1.30	

[a] Pimentel and Pimentel (1996).

[b] It is assumed that a person works 2000 h per year and utilizes an average of 8100 L of oil equivalents per year.

[c] Farm labor costs were estimated to be $10 per hour.

[d] Pimentel (1980).

[e] Hinman et al. (1992).

[f] USDA (1997a,b).

[g] FAO (1999).

[h] Sulfuric acid production is an exothermic process. The cost of sulfuric acid was $73.00/ha (cking@micron.net).

[i] 30¢/kg of goods transported (USDA, 1998).

[j] Pimentel et al. (1993).

[k] Price of electricity is 7¢ per kWh (USBC, 1998).

[l] A sum of the quantity values for machinery, fuels, and seeds (all converted to mass units).

In an intensive potato production system, production per hectare is several times greater than that of other carbohydrate-producing crops. More importantly, protein production per hectare is two to three times greater than most other crops.

Based on U.S. data, the largest energy inputs are for machinery and fuel and the second largest input is for fertilizers (Table 12.8). The total energy inputs are about 71.8 GJ/ha with a yield of about 38,820 kg/ha (93.4 GJ of food energy) (Table 12.9). The resulting input/output ratio is 1:1.30. Note that the high water content of potatoes (80%) makes transport relatively energy costly, compared with grain crops.

TABLE 12.9
Energy Inputs and Costs of Cassava Production per Hectare in Thailand, Colombia, Vietnam, and Nigeria

Inputs	Quantity	MJ	Costs ($)
Labor	1,632 h[a]	22,621[b]	93.42[a]
Draft animal (buffalo)	200 h[c]	2,079[d]	9.64[e]
Machinery	5 kg[c]	391[f]	3.83[a]
Nitrogen	46 kg[a]	3,591[g]	28.52[h]
Phosphorus	33 kg[a]	567[g]	18.15[h]
Potassium	43 kg[a]	588[g]	13.33[h]
Manure, organic	3,400 kg[a]	23,684[d]	10.00[c]
Cassava sticks	6,000 sticks (120 bundles)[i]	1,126[j]	40.00[k]
Total		54,647	216.89
Yield 12,360 kg[a]		196,510	
		kcal input/output = 1:3.60	

[a] CIAT (1996).

[b] It is estimated that each person uses about 600 L of oil equivalents per year. This is based on the average per capita use of fossil energy in Central and South America (British Petroleum, 1999).

[c] Estimated.

[d] Tripathi and Sah (2001).

[e] CIAT (1996).

[f] Pimentel (1980).

[g] FAO (1999).

[h] Hinman et al. (1992).

[i] Estimates are that it takes about 8 days to collect cassava sticks for planting.

[j] Energy input was calculated based on information in CIAT (1996).

[k] Ezeh (1988).

CASSAVA

Cassava is a major food crop worldwide, especially in Africa, Asia, and Latin America, and can be grown in soils of low fertility. It is one of the highest producing crops in terms of carbohydrate per hectare, but is one of the lowest in terms of protein per hectare.

The data for cassava production are from Thailand, Colombia, Nigeria, and Vietnam (Table 12.9). The labor input in the cassava system is relatively high or 1632 h/ha, and the average yield is 12,360 kg/ha (196.5 GJ/ha). With an energy input of 54.6 GJ/ha, the resulting input/output ratio is 1:3.60 (Table 12.9).

SWEET POTATOES

Along with the white potato and cassava, the sweet potato is another major food crop, especially in the tropics. In addition to carbohydrate, the sweet potato is high in vitamin A, iron, and abundant carbohydrate.

TABLE 12.10
Energy and Economic Costs of Various Crops Produced in Several Developing and Developed Countries (per hectare) (Pimentel et al., 2001)

Crop	Country	Energy Harvest Yield (kg)	MJ	Labor (h)	Labor Input (MJ)	Energy Input (MJ)	Economic Costs ($)	kcal Input/ Output
Soybean	Philippines	988	16,724	744	5,498	11,315	310.58	1:1.47
Potato	Philippines	5,500	13,238	1400	10,349	31,844	655.60	1:0.42
Sweet potato	Vietnam	11,867	49,841	1678	12,403	24,776	908.73	1:2.01
Cabbage	United States	38,416	81,320	60	11,227	46,230	1341.08	1:1.76
Cabbage	India	11,423	24,184	1834	10,781	45,913	206.95	1:0.53
Tomato	United States	55,000	46,301	363	61,236	136,034	7337.42	1:0.34
Tomato	Pakistan	14,767	12,403	2337	8,585	13,184	1746.73	1:0.94
Orange	United States	46,056	98,780	210	39,287	96,269	3048.55	1:1.03
Apple	United States	54,743	128,755	385	72,030	210,817	7724.53	1:0.61
Apple	India	6,000	14,112	610	3,944	9,110	81.29	1:1.55
Corn, irrig.	United States	7,965	120,431	10	1,869	112,736	1674.88	1:1.07

The production of sweet potato in the Red River Delta, Vietnam, requires 1678 h/ha of labor, plus relatively large inputs of fertilizers (Table 12.10). The average yield is 11,867 kg/ha, providing 49.8 GJ/ha of food energy. The energy input in this system is 24.8 GJ/ha, resulting in an input/output ratio of 1:2.01 (Table 12.10).

COLE CROPS

Cole crops, such as cabbage, are grown worldwide and are excellent sources of nutrients, including vitamin A, vitamin C, and iron. Typical of U.S. vegetable production, the major energy inputs are for machinery and fuel, with fertilizers being the second largest input (Table 12.10). The average yield is 38,416 kg/ha, providing 81.3 GJ/ha. The total energy input is 46.2 GJ/ha and the resulting input/output ratio is 1:1.76 (Table 12.10).

In contrast, cabbage production in the Garhwal Himalaya region of India requires 1831 h/ha of labor and 294 h/ha of bullock power (Tripathi and Sah, 2001) (Table 12.10). The total energy input is 45.9 GJ/ha or similar to that for U.S. cabbage production (Table 12.10). With a total yield of cabbage in India of 11,423 kg/ha (24.2 GJ), the resulting input/output ratio is 1:0.53 (Table 12.10).

TOMATOES

Tomatoes are valued for their vitamin C (23 mg per 100 g of fresh tomato), vitamin A, and iron. In the United States labor input for tomato production is relatively high, or about 363 h/ha (Table 12.10). The fossil energy inputs are 136.0 GJ, primarily expended for machinery, fuel, and fertilizers. The tomato yield of 55,000 kg/ha provides 46.3 GJ of food energy, with the resulting input/output ratio of 1:0.34 (Table 12.10).

Based on data from Pakistan, the major input for tomato production is labor (2337 h/ha) (Haq et al., 1997) (Table 12.10). The tomato yield is about 14,767 kg/ha, providing nearly 12.4 GJ of food energy and a resulting input/output ratio of 1:0.94 that is more than double that in the United States.

ORANGES

Oranges are a valuable fruit in U.S. agriculture, costing about $3000 per hectare for production (Table 12.10). Although per hectare oranges and other citrus fruits provide more than double the vitamin C content of white potatoes, U.S. citizens obtain half of their vitamin C from white potatoes and half from citrus (USDA, 2000). The production of oranges requires the expenditure of 96.3 GJ/ha of fossil energy (Table 12.10). Based on the orange yield of 46,065 kg/ha the food energy is 98.8 GJ, resulting in an input/output ratio of 1.03.

APPLES

Apples are another economically valuable crop in the United States costing about $7725 per hectare to produce (Table 12.10). The energy input used in orchards is primarily for machinery (Table 12.10), while pesticides contribute nearly 20% of the total energy input.

Also the labor input of 385 h/ha in apple production, especially during harvest, is high compared with most other food crops grown in the United States. The total labor input is about 72.0 GJ/ha of the total of 210.8 GJ of energy expended (Table 12.10). Based on the total apple yield of 54,743 kg/ha, this provides 128.8 GJ of food energy, with an input/output ratio of 1:0.61.

Apple production in the high hills of the Garhwal Himalaya region of India requires 610 h of labor, nearly twice that of the United States (Tripathi and Sah, 2001) (Table 12.10). Although the apple yield in India is only 6000 kg/ha (14.1 GJ/ha), this is a much more favorable input/output ratio of 1:1.57 (Table 12.10). The reason is fewer fossil energy inputs.

IRRIGATED CROPS

Producing food crops employing irrigation requires enormous amounts of water plus the expenditure of fossil energy to pump and apply the freshwater (Postel, 1999). For example, a corn crop grown in an arid region requires about 1000 mm of irrigated water per hectare (Falkenmark and Lindh, 1993). To pump the water from a depth of only 30.5 m (100 feet) and apply it requires about 112.8 GJ of fossil energy per hectare (Table 12.10).

The total energy input for irrigated corn amounts to 29.6 GJ for rainfed corn compared with 112.8 GJ for irrigated corn, or three times the energy needed for rainfed corn (Tables 12.2 and 12.10).

In addition to increased energy for irrigation, overall economic costs of production also rise in an irrigated production system because of the high costs of pumping water (Tables 12.2 and 12.10).

ECONOMICS OF FOOD CROP PRODUCTION

The price value at the farm gate of the 10 crops in developing countries and 9 crops assessed in developed countries averages about 12¢ per kg (see tables). Oranges are not included in the developing country calculation and sweet potato and cassava are not included in the developed country calculation.

Corn is produced more cheaply in Indonesia (5¢/kg) than in the United States (11¢/kg), and rice is produced more cheaply in India (11¢/kg) than in the United States (21¢) (Pimentel et al., 2001). Wheat production costs are 11¢/kg in India and 16¢/kg in the United States (Tables 12.3 and 12.4).

Soybeans and potatoes cost more to produce in the Philippines than in the United States (Pimentel et al., 2001). Also, tomatoes are more costly to produce in Pakistan than in the United States. However, apple production is far more expensive in the United States than in India (Pimentel, 2001), because of large inputs of labor and other inputs in the U.S. apple system.

Compared with developed nations, farm wages are extremely low in developing countries, ranging from 6¢ to 50¢ per hour. Yet, labor is the primary cost for food production in developing countries because of the great number of hours invested, ranging from 600 to 1800 h/hectare in production (see tables). The primary costs in U.S. food crop production are for mechanization, fertilizers, and pesticides. The cost of irrigation is two to three times the cost of all the other inputs in U.S. food crop production (Pimentel and Pimentel, 1996).

No data were presented concerning the relative incomes and purchasing power of people in each nation, and this significantly changes the perspectives in each nation.

CHANGES IN WORLD FOOD CROP PRODUCTION

Fossil Energy Use and Crop Yields

Since about 1950 when the availability of fossil energy became readily available, especially in developed nations, this supported the 20- to 50-fold increase in the use of fertilizers, pesticides, and irrigation. From 1950 to 1980, U.S. grain production per hectare increased three to four times (USDA, 1980). For example, where fertilizer use on corn increased from about 5 kg/ha in 1945 to about 150 kg/ha (30 times), corn yields increased by about four times (Pimentel and Pimentel, 1996). The rate of yield increases during the 30-year period from 1950 to 1980 was about 3% per year. However, since 1980, U.S. grain crop yield increases declined to only about 1% per year (USDA, 1980). This is because crops have limits to the amounts of fertilizers and pesticides that they can tolerate and use. In fact, nitrogen fertilizer application rates of approximately 500 kg/ha or more are toxic and cause crop yields to decline (Martinez and Guiraud, 1990).

The significant achievement of using fossil energy to increase crop yields, and cereal grains in particular, started in 1950 with the advent of the Green Revolution (Conway, 1997). During the 1950s, plant breeders developed wheat, rice, corn, and other cereal crops to have short statures so that large quantities of fertilizers, especially nitrogen, could be applied in production. The short stature was essential to prevent the plants from growing and then falling over (lodging), which formerly resulted in a loss of the crop.

The availability and use of fossil fuels also was instrumental in the success of the Green Revolution. During the 1950s, plant geneticists developed rice, wheat, and other major grain crops to have short stature that facilitated the heavy application of fertilizers, especially nitrogen (Conway, 1997). As a result, crop yields per hectare were significantly increased for the newly developed grains. Yet, in 75 countries, less grain was produced by 1990 than at the beginning of the decade (Dasgupta, 1998).

At best, world grain yields per hectare are slowly increasing, at the most about 1% per year, while human population numbers and their food needs are increasing at a greater rate than food production can supply their needs (Pimentel et al., 1999). As the world population increases it outstrips increases in food production. Thus, it is becoming more apparent that the food supply cannot keep up with the needs of a rapidly increasing human population.

On a per capita basis, world grain production has declined since 1984 (FAO, 1961–2001). Grains make up about 80% of the world food crops. Shortages of the basic resources for a productive crop system now currently exist. These worldwide losses in fertile cropland, loss of freshwater, and diminishing fossil energy supplies used in mechanization, fertilizers, pesticides, and irrigation are having negative impacts on crop production.

Per capita use of fertilizers worldwide during the past decade declined 17% (Worldwatch, 2001), while available cropland resources per capita decreased more than 20% (Pimentel et al., 1999). A total of 560 million ha of the 1500 million ha of cropland worldwide has been seriously degraded because of soil erosion (Greenland et al., 1998).

Irrigated land area in developing countries declined about 10% over the past decade (Postel, 1999). A total of 20% of the irrigated croplands worldwide suffer from salinization—a result of poor irrigation and drainage practices (Greenland et al., 1998).

FOSSIL ENERGY USE IN CROP PRODUCTION

Of the total fossil energy consumed in the world of about 384 quads, approximately 270 quads are used in developed countries and 114 quads in developing countries. The population in developed countries is less than 2 billion while more than 4 billion live in developing countries (PRB, 2000).

Developed countries use approximately 40 quads of fossil energy, but only about 16 quads of this are used directly for both crop and livestock production (Pimentel and Pimentel, 1996). The remaining 24 quads are used for food processing, packaging, distribution, and preparation.

In contrast, in developing countries approximately 28 quads are consumed in agricultural production. Little fossil energy is used in cooking because biomass energy (fuelwood, crop residues, and dung) is the prime fuel (Pimentel and Pimentel, 1996). From 2 to 3 kcal of biomass energy are used to prepare 1 kcal of food in developing countries (Pimentel and Pimentel, 1996; Tripathi and Sah, 2001). Therefore, total energy in the food system in developed and developing countries is about 68 quads per year.

Crop production in both developed and developing countries requires from 7.7 to 210.8 GJ/ha (see tables). In developed countries, the fossil energy inputs for machinery to reduce the labor input are high, whereas in the developing countries the fossil energy inputs for labor are high (see tables). Fossil energy inputs for labor are listed in terms of per capita fossil fuel consumption. Most of the fossil energy used in world food production is oil for farm machinery and pesticides while natural gas is vital for the production of nitrogen fertilizers.

The total energy expended in the food system of developed countries is approximately 5 J to supply 1 J of food, while in developing countries the ratio is approximately 4 J invested to supply 1 J of food (see tables). In developed countries people consume an average of 3400 kcal of food per person per day, whereas people in developing countries consume 2400 kcal of food per day per person (FAO, 1999a). This 1000 fewer kcal consumed per person per day in developing countries reflects in part the lower the total fossil energy inputs in their food system.

RENEWABLE ENERGY

The United States is currently consuming about 91 quads (24%) of the world's 384 quads expenditure of fossil energy (British Petroleum Statistical Review of World Energy, 1999; USBC, 1998). Best estimates are that about half (45 quads) of the current fossil energy consumption in the United States could be produced by employing an array of renewable energy technologies (Pimentel et al., 1994).

Liquid fuel needs for tractors and other farm machinery might be met using hydrogen or pyrolytic oil produced from wood (Pimentel et al., 1994, 2001). Nitrogen can be produced using electrical discharge to convert atmospheric nitrogen to nitrate. However, about 200,928 J of energy are required to produce 1 kg of nitrogen by this method, compared to 78,078 J required using fossil energy dependent technologies (Treharne and Jakeway, 1980; FAO, 1999b). Based on current renewable energy technologies, a quantity of energy produced using renewable technologies costs from 5 to 10 times more than an equivalent amount obtained from fossil energy sources.

FUTURE TECHNOLOGIES

In the past decades, advances in science and technology have been instrumental in increasing industrial and agricultural production, improving transportation and communications, advancing human health care, and in general improving many aspects of human life. However, much of this success is based on the availability of resources in the natural ecosystems of the Earth.

Technology cannot produce an unlimited flow of the vital natural resources that are the raw material for sustained agricultural production. Genetic engineering holds promise, provided that its genetic transfer ability is wisely used. For example, the genetic modification of some crops, such as rice, to have high levels of iron and beta-carotene would improve the nutrition of millions of people in the future, particularly those in developing countries where rice is the prime grain consumed (Friedlander, 2000). In addition, the possibility exists for biological nitrogen fixation to be incorporated in crops, such as corn and wheat. Hopefully improved technologies, including the more effective management and use of resources, will help increase food production.

Yet there are limitations to what technology can accomplish. In no area is this more evident than in agricultural production. No known or future technology could, for example, double the quantity of the world's fertile cropland available for production. Granted, synthetically produced fertilizers are effective in enhancing the fertility of eroded croplands, but their production relies on sustained supplies of finite fossil fuels. Thus, in countries like the United States and China farmers can be expected to experience rapidly diminishing returns with the further application of fertilizers.

To date, biotechnology that started more than 20 years ago has not stemmed the decline in per capita food production during the past 17 years. Currently, more than 40% of the genetic engineering research effort is devoted to the development of herbicide resistance in crops (Paoletti and Pimentel, 1996). This herbicide-tolerance technology has not increased crop yields, but instead generally increased the use of chemical herbicides and polluted the environment. Indeed, this technology could eventually result in increasing labor and decreasing crop yields as weed species acquire additional herbicide-resistance (Paoletti and Pimentel, 1996).

SUMMARY

Based on the information presented, if current trends in human population growth and fossil fuel consumption continue into the future, projections for the adequacy of tomorrow's world food supply are not encouraging. When the world population expands to nearly 8 billion as projected in about 15 years, food yields will have to increase 33% (Greenland et al., 1998). The factors that govern our success in achieving this are dependent on our dedication to conservation and judicious use of our natural resources, increasing political and economic stability, and most vital, reducing the world population (Pimentel et al., 1999). The basic equation of people versus food and energy intensifies the imbalances between the human food supply and the natural resource needs of a rapidly growing world population.

REFERENCES

Ali, M. and W.D. McBride. 1999. *Soybeans: Cost of Production, 1990.* http://usda.mannlib.cornell.edu/data-sets/crops/p4009/.

Arama, P.F. 1994. Breeding and selection of bread wheat to *Septoria tritici* Blotch, *Current Plant Science and Biotechnology in Agriculture; Durability of Disease Resistance* 18: 191.

Bartlett, A.A. and R.A. Ristinen. 1995. Natural gas and transportation. *Physics and Society* 24: 9–10.

British Petroleum. 1999. *British Petroleum Statistical Review of World Energy.* London: British Petroleum Corporate Communications Services.

Campbell, C.J. 1997. *The Coming Oil Crisis.* New York: Multi-Science Publishing Company & Petroconsultants S.A.

CIAT. 1996. *Cassava Production, Processing, and Marketing in Vietnam.* Proceedings of Workshop, Hanoi, Vietnam, October 29–31, 1992, Howler, R.H. (ed.), Bangkok, Thailand. cking@micron.net, December 2, 1999.

College of Agricultural, Consumer and Environmental Sciences. 1997. *Machinery Cost Estimates: Summary of Operations*, University of Illinois at Urbana-Champaign, http://web.aces.uinc.edu/fbfm/farmmagmt.htm.

Conway, G. 1997. *The Doubly Green Revolution, Food for All in the Twenty-First Century.* London: Penguin.

Dasgupta, P. 1998. The economics of food. In D.G. Waterlow, L.F. Armstrong, and R. Riley (eds.), *Feeding a World Population of More Than Eight Billion People*, pp. 19. New York: Oxford University Press.

Djauhari, A., A. Djulin, and I. Soejono. 1988. *Maize Production in Java: Prospects for Improved Farm-Level Production Technology.* Indonesia: CGPRT Centre.

DOE. 1991. *Annual Energy Outlook with Projections to 2010.* Washington, D.C.: Energy Information Administration, U.S. Department of Energy.

Doering, O.C. 1980. Accounting for energy in farm machinery and buildings. In D. Pimentel (ed.), *Handbook of Energy Utilization in Agriculture*, pp. 9–14. Boca Raton, FL: CRC Press.

Doughty, R.S. 2000. Unpublished.

Duncan, R.C. 2001. World energy production, population growth, and the road to the Olduvai Gorge. *Population and Environment* 22: 503.

Economic Research Statistics. 1997. *Soybeans: Fertilizer Use by State, 1996.* http://usda.mannlib.cornell.edu/data-sets/inputs/9X171/9717/agch0997.txt.

Ezeh, N. 1988. Comparative economic analysis of NAFPP and traditional cassava/maize production technologies in Rivers State of Nigeria. *Agricultural Systems* 27: 225.

Falkenmark, M. and G. Lindh. 1993. Water and economic development. In P. Gleick (ed.), *Water in Crisis: A Guide to the World's Fresh Water Resources*, pp. 80–91. Oxford: Oxford University Press.

FAO. 1961–2001. *Quarterly Bulletin of Statistics*. Food and Agriculture Organization, United Nations, Rome, Italy.

FAO. 1997. *Quarterly Bulletin of Statistics*. Food and Agriculture Organization, United Nations, Rome, Italy, 10.

FAO. 1999a. *Food Balance Sheets*. Food and Agriculture Organization. United Nations, Rome, Italy.

FAO. 1999b. *Agricultural Statistics*, http://apps.fao.org/cgi-bin/nph-db.pl?subset-agriculture. Food and Agriculture Organization, United Nations.

Fluck, R.C. 1992. Energy of human labor. In R.C. Fluck (ed.), *Energy in World Agriculture*, pp. 31–37. Amsterdam, the Netherlands: Elsevier.

Friedlander, B.P. 2000. Genetically engineered food could be lifeline for developing world. Environmental News Network. wysiwyg:/21//http//www.enn.com/direct/displayrelease.asp?id=895

Giampietro, M. and D. Pimentel. 1990. Assessment of the energetics of human labor. *Agriculture, Ecosystems and Environment* 32: 257–272.

Greenland, D.J., P.J. Gregory, and P.H. Nye. 1998. Land resources and constraints to crop production. In D.G. Waterlow, L.F. Armstrong, and R. Riley (eds.), *Feeding a World Population of More Than Eight Billion People*, pp. 39. New York: Oxford University Press.

Haq, Z.U., S. Saddozal, H. Jahkanzeb, et al. 1997. Economics of inter cropping: A case study of tomato production in garlic in District Nowshera. *Sarhad Journal of Agriculture* 13: 1997.

Hassan, R.M., W. Mwangi, and D. Karanja. 1993. Wheat supply in Kenya: Production technologies, sources of inefficiency, and potential for productivity growth. *CIMMYT Economics Working Papers* 93-02.

Hinman, H., G. Pelter, E. Kulp, et al. 1992. Enterprise budgets for fall potatoes, winter wheat, dry beans, and seed peas under rill irrigation. Farm Business Management Reports, Columbia County, Washington State University, Pullman, WA.

Hinman, H. and R. Schiriman. 1997. Enterprise budgets, summer fallow—winter wheat—spring barley rotation. Columbia County, Washington State University, Pullman, WA.

Hoffman, T.R., W.D. Warnock, and H.R. Hinman. 1994. Crop enterprise budgets, Timothy-legume and alfalfa hay, Sudan grass, sweet corn and spring wheat under rill irrigation, Kittitas County, Washington. Farm Business Reports EB 1173, Washington State University, Pullman, WA.

International Energy Annual. 1996. DOE/EIA-0220[96]. Washington, D.C.: U.S. Department of Energy.

Ivanhoe, L.F. 2000. World oil supply—production, reserves, and EOR. *Hubbert Center Newsletter* # 2000/1-1.

Kuesters, J. and J. Lammel. 1999. Investigations of the energy efficiency of the production of winter wheat and sugar beet in Europe. *European Journal of Agronomy* 11: 35–43.

Longmire, J. and J. Lugogo. 1989. The economics of small-scale wheat production technologies for Kenya. *CIMMYT Working Papers* 89/01.

Martinez, J. and G. Guiraud. 1990. A lysimeter study of the effects of a ryegrass catch crop during a winter wheat–maize rotation on nitrogen leaching and on the following crop. *Journal of Soil Science* 41: 5–16.

McGuckin, J.T., N. Gollehon, and S. Ghosh. 1992. Water conservation in irrigated agriculture: A stochastic production frontier model. *Water Resources Research* 28: 305–312.

Myer, B. 1997. *Sulfur, Energy and Environment*. New York: Elsevier Scientific Publishing Company.

National Agricultural Statistics Service. 1997. *Agricultural Chemical Usage 1996 Field Crops Summary*, Washington, D.C.: U.S. Department of Agriculture, Economic Research Service.

National Agricultural Statistics Service. 1999. *Farm Labor.* National Agricultural Statistics Service, http://usda.mannlib.cornell.edu (December 1999).

Paoletti, M.G. and D. Pimentel. 1996. Genetic engineering in agriculture and the environment. *BioScience* 46: 665–673.

Pimentel, D. 1980. *Handbook of Energy Utilization in Agriculture.* Boca Raton, FL: CRC Press.

Pimentel, D., L. McLaughlin, A. Zepp, et al. 1993. Environmental and economic effects of reducing pesticide use in agriculture. *Agriculture Ecosystems & Environment* 46: 273–288.

Pimentel, D., T. Rodrigues, R. Wang, et al. 1994. Renewable energy: Economic and environmental issues. *BioScience* 44: 536–547.

Pimentel, D. and M. Pimentel. 1996. *Food, Energy and Society.* Boulder, CO: Colorado University Press.

Pimentel, D., O. Bailey, P. Kim, et al. 1999. Will the limits of the Earth's resources control human populations? *Environment, Development and Sustainability* 1: 19–39.

Pimentel, D., R. Doughty, C. Carothers, et al. 2001. Energy inputs in crop production in developing and developed countries*,* Environmental Biology Report 01-2.

Population Summit of the World's Scientific Academies, 1994. National Academy of Sciences Press, Washington, D.C.

Postel, S. 1999. *Pillar of Sand: Can the Irrigation Miracle Last?* New York: W.W. Norton.

PRB. 2000. *World Population Data Sheet.* Washington, D.C.: Population Reference Bureau.

Surendra, S., P.S. Madhu, R.S. Rana, et al. 1989. Energy and cost regulation for cultivation of rice (*Oryza sativa*)—wheat (*Tritichum aestivum*)—maize (*Zea mays*)—wheat rotations. *Indian Journal of Agricultural Science* 59: 558.

Treharne, R.W. and L. Jakeway. 1980. Research and development of fertilizer production using renewable energy sources. *American Society of Agricultural Engineers* PR 80–41: 3.

Tripathi, R.S. and V.K. Sah. 2001. Material and energy flows in high-hill, mid-hill and valley farming systems of Garhwal Himalaya. *Agriculture, Ecosystems and Environment* 86: 75–91.

Tsatsarelis, C.A. 1993. Energy inputs and outputs for soft winter wheat production in Greece. *Agriculture, Ecosystems and Environment* 43: 109–118.

United Soybean Board. 1999. *Soybean Yield by State 1998.* http://206.168.118.237/99soystats/page18.htm.

UNU/INRA. 1999. *World Food Day, 16 October 1999.* The United Nations University, Institute of Natural Resources in Africa.

USBC. 1998. *Statistical Abstract of the United States 1996*, 200th ed. U.S. Bureau of the Census. Washington, D.C.: U.S. Government Printing Office.

USDA. 1980. *Agricultural Statistics 1981.* U.S. Department of Agriculture, Washington, D.C.: U.S. Government Printing Office.

USDA. 1991. *Corn-State. Costs of Production.* U.S. Department of Agriculture, Economic Research Service, Economics and Statistics System, Washington, D.C., Stock #94018.

USDA. 1997a. Agricultural Resources and Environmental Indicators, *Agricultural Handbook*, U.S. Department of Agriculture, Economic Research Service, Natural Resources and Environmental Division, Washington, D.C.: 712.

USDA. 1997b. *National Agricultural Statistics Service.* Washington, D.C.: U.S. Department of Agriculture, Economic Research Service.

USDA. 1998. *Farm Business Briefing Room 1998.* Washington, D.C.: U.S. Department of Agriculture.

USDA. 1998. *Agricultural Statistics*. Washington, D.C.: U.S. Department of Agriculture.

USDA. 1999a. *Agricultural Statistics*. Washington, D.C.: U.S. Department of Agriculture.

USDA. 1999b. *Agricultural Prices, 1998 Summary*. Washington, D.C.: U.S. Department of Agriculture, National Agricultural Statistics Service.

USDA. 2000. *Agricultural Statistics*. Washington, D.C.: U.S. Department of Agriculture.

Wen, D. and D. Pimentel. 1992. Ecological resource management to achieve a productive, sustainable agricultural system in northeast China. *Agriculture, Ecosystems and Environment* 41: 215–230.

WHO. 1996. *Micronutrient Malnutrition—Half of the World's Population*. World Health Organization 78: 1.

Willet, G.S. and W.G. Gary. 1997. Enterprise budgets, summer fallow—winter wheat—spring barley rotation. Columbia County, Washington State*, Farm Business Reports*, Pullman, WA: Washington State University.

Worldwatch. 2001. *Vital Signs 2001*. New York: W.W. Norton & Company.

www.fertilizer.org/PUBLISH/PUBMAN/cassava.htm (October 15, 1999).

Youngquist, W. 1997. *Geodestinies: The Inevitable Control of Earth Resources over Nations and Individuals*. Portland, OR: National Book Company.

13 Environmental and Economic Costs of the Application of Pesticides Primarily in the United States

Worldwide, about 3 billion kg of pesticides are applied each year with a purchase price of nearly \$40 billion per year (Pan-UK, 2003). In the United States, approximately 500 million kg of more than 600 different pesticide types are applied annually at a cost of \$10 billion (Pimentel and Greiner, 1997).

Despite the widespread application of pesticides in the United States at recommended dosages, pests (insects, plant pathogens, and weeds) destroy 37% of all potential crops (Pimentel, 1997). Insects destroy 13%, plant pathogens 12%, and weeds 12%. In general, each dollar invested in pesticide control returns about \$4 in protected crops (Pimentel, 1997).

Although pesticides are generally profitable in agriculture, their use does not always decrease crop losses. For example, despite the more than 10-fold increase in insecticide (organochlorines, organophosphates, and carbamates) use in the United States from 1945 to 2000, total crop losses from insect damage have nearly doubled from 7% to 13% (Pimentel et al., 1991). This rise in crop losses to insects is, in part, caused by changes in agricultural practices. For instance, the replacement of corn–crop rotations with the continuous production of corn on more than half of the corn acreage has nearly resulted in an increase in corn losses to insects from about 3.5% to 12% despite a more than 1000-fold increase in insecticide (organophosphate) use in corn production (Pimentel et al., 1991). Corn today is the largest user of insecticides of any crop in the United States.

Most benefits of pesticides are based on the direct crop returns. Such assessments do not include the indirect environment and economic costs associated with the recommended application of pesticides in crops. To facilitate the development and implementation of a scientifically sound policy of pesticide use, these environmental and economic costs must be examined. For several decades, the U.S. Environmental Protection Agency (EPA, 1977) pointed out the need for such a benefit/cost and risk investigation. Thus far, only a few scientific papers on this complex and difficult subject have been published.

PUBLIC HEALTH EFFECTS

ACUTE POISONINGS

Human pesticide poisonings and illnesses are clearly the highest price paid for all pesticide use. The total number of pesticide poisonings in the United States is estimated to be 300,000 per year (EPA, 1992). Worldwide, the application of 3 million metric tons of pesticides results in more than 26 million cases of nonfatal pesticide poisonings (Richter, 2002). Of all the pesticide poisonings, about 3 million cases are hospitalized and there are approximately 220,000 fatalities and about 750,000 chronic illnesses every year (Hart and Pimentel, 2002).

CANCER AND OTHER CHRONIC EFFECTS

Ample evidence exists concerning the carcinogenic threat related to the use of pesticides. These major types of chronic health effects of pesticides include neurological effects, respiratory and reproductive effects, and cancer. There is some evidence that pesticides can cause sensory disturbances as well as cognitive effects such as memory loss, language problems, and learning impairment (Hart and Pimentel, 2002). The malady, organophosphate induced delayed poly-neuropathy (OPIDP), is well documented and includes irreversible neurological damage.

In addition to neurological effects, pesticides can have adverse effects on the respiratory and reproductive systems. For example, 15% of a group of professional pesticide applicators suffered asthma, chronic sinusitis, and chronic bronchitis (Weiner and Worth, 1972). Studies have also linked pesticides with reproductive effects. For example, some pesticides have been found to cause testicular dysfunction or sterility (Colburn et al., 1996). Sperm counts in males in Europe and the United States, for example, declined by about 50% between 1938 and 1990 (Carlsen et al., 1992). Currently, there is evidence that human sperm counts continue to decrease by about 2% per year (Pimentel and Hart, 2001).

U.S. data indicate that 18% of all insecticides and 90% of all fungicides are carcinogenic (NAS, 1987). Several studies have shown that the risks of certain types of cancers are higher in some people, such as farm workers and pesticide applicators, who are often exposed to pesticides (Pimentel and Hart, 2001). Certain pesticides have been shown to induce tumors in laboratory animals and there is some evidence that suggest similar effects occur in humans (Colburn et al., 1996).

A United Farm Workers (UFW) (2003) study of the cancer registry in California analyzed the incidence of cancer among Latino farm workers and reported that per year, if everyone in the United States had a similar rate of incidence, there would be 83,000 cases of cancer associated with pesticides in the United States. The incidence of cancer in the U.S. population due to pesticides ranges from about 10,000–15,000 cases per year (Pimentel et al., 1997).

Many pesticides are also estrogenic—they mimic or interact with the hormone estrogen—linking them to increase in breast cancer among some women. The breast cancer rate rose from 1 in 20 in 1960 to 1 in 8 in 1995 (Colburn et al., 1996). As expected, there was a significant increase in pesticide use during that time period.

Pesticides that interfere with the body's endocrine—hormonal—system can also have reproductive, immunological, or developmental effects (McCarthy, 1993). While endocrine disrupting pesticides may appear less dangerous because hormonal effects rarely result in acute poisonings, their effects on reproduction and development may prove to have far-reaching consequences (Colburn et al., 1996).

The negative health effects of pesticides can be far more significant in children than adults, for several reasons. First, children have higher metabolic rates than adults, and their ability to activate, detoxify, and excrete toxic pesticides differs from adults. Also, children consume more food than adults and thus can consume more pesticides per unit weight than adults. This problem is particularly significant for children because their brains are more than five times larger in proportion to their body weight than adult brains, making chloinesterase even more vital. In a California study, 40% of the children working in agricultural fields had blood cholinesterase levels below normal, a strong indication of organophosphate and carbamate pesticide poisoning (Repetto and Baliga, 1996). According to the EPA, babies and toddlers are 10 times more at risk for cancer than adults (Hebert, 2003).

Although no one can place a precise monetary value on a human life, the economic "costs" of human pesticide poisonings have been estimated (Table 13.1). For our assessment, we use the EPA standard of $3.7 million per human life (Kaiser, 2003). Available estimates suggest that human pesticide poisonings and related illnesses in the United States cost about $1 billion per year (Pimentel and Greiner, 1997).

TABLE 13.1

Estimated Economic Costs of Human Pesticide Poisonings and Other Pesticide-Related Illnesses in the United States Each Year

Human Health Effects from Pesticides	Total Costs ($)
Cost of hospitalized poisonings	
5000[a] × 3 days @ $2000/day	30,000,000
Cost of outpatient treated poisonings	
30,000[b] × $1000[c]	30,000,000
Lost work due to poisonings	
5000[a] workers × 5 days × $80	2,000,000
Pesticide cancers	
10,000[b] × $100,000/case	1,000,000,000
Cost of fatalities	
45 accidental fatalities[a] × $3.7 million	166,500,000
Total	1,228,500,000

[a] Estimated.

[b] See text for details.

[c] Includes hospitalization, foregone earnings, and transportation.

Source: Pimentel, D., *Environment, Development and Sustainability*, 7, 229–252, 2005. With permission of Springer Science and Business Media.

PESTICIDE RESIDUES IN FOOD

The majority of foods purchased in supermarkets have detectable levels of pesticide residues. For instance, of several thousand samples of food, the overall assessment in 8 fruits and 12 vegetables is that 73% have pesticide residues (Baker et al., 2003). In five crops (apples, peaches, pears, strawberries, and celery) pesticide residues were found in 90% of the crops. Of interest is the fact that 37 different pesticides were detected in apples (Groth et al., 1999).

Up to 5% of the foods tested in 1997 contained pesticide residues that were above the Food and Drug Administration (FDA) tolerance levels. Although these foods violated the U.S. tolerance of pesticide residues in foods, these same foods were consumed by the public. This is because the food samples were analyzed after the foods were sold in the supermarkets.

DOMESTIC ANIMAL POISONINGS AND CONTAMINATED PRODUCTS

In addition to pesticide problems that affect humans, several thousand domestic animals are accidentally poisoned by pesticides each year, with dogs and cats representing the largest number (Table 13.2). For example, of 250,000 poison cases involving animals, a large percentage were related to pesticides (National Animal Poison Control Center, 2003). Poisoning of dogs and cats are common. This is not surprising because dogs and cats usually wander freely about the home and farm and therefore have greater opportunity to come into contact with pesticides than other domesticated animals.

The best estimates indicate that about 20% of the total monetary value of animal production, or about $4.2 billion, is lost to all animal illnesses, including pesticide poisonings. It is reported that 0.5% of animal illnesses and 0.04% of all animal deaths reported to a veterinary diagnostic laboratory were due to pesticide toxicosis. Thus, $21.3 and $8.8 million, respectively, are lost to pesticide poisonings (Table 13.2).

This estimate is considered low because it is based only on poisonings reported to veterinarians. Many animal deaths that occur in the home and on farms go undiagnosed and unreported. In addition, many are attributed to other factors than pesticides. Also, when a farm animal poisoning occurs and little can be done for the animal, the farmer seldom calls a veterinarian but rather either waits for the animal to recover or destroys it. Such cases are usually unreported.

Additional economic losses occur when meat, milk, and eggs are contaminated with pesticide. In the United States, all animals slaughtered for human consumption, if shipped interstate, and all imported meat and poultry, must be inspected by the United States Department of Agriculture (USDA). This is to ensure that the meat and products are wholesome, properly labeled, and do not present a health hazard.

Pesticide residues are searched for in animals and their products. However, of the more than 600 pesticides in use now, the National Residue Program (NRP) only searches for about 40 different pesticides, which have been determined by FDA, EPA, and Food and Safety Inspection Service (FSIS) to be of public health concern. While the monitoring program records the number and type of violations, there

TABLE 13.2
Estimated Domestic Animal Pesticide Poisonings in the United States

Livestock	Number × 1000	$ per Head	Number Ill[a]	$ Cost per Poisoning[b]	$ Cost of Poisonings	Number of Deaths[c]	$ Cost of Deaths × 1000[d]	Total $ × 1000
Cattle	99,000[e]	607[e]	100	121.40	12,140	8	4,856	16,996
Dairy cattle	10,000[e]	900[e]	10	180.00	1,800	1	900	2,700
Dogs	55,000[f]	125[g]	55	25.00	1,375	4	500	1,875
Horses	11,000[d]	1000[f]	11	200.00	2,200	1	1,000	3,200
Cats	63,000[f]	20[g]	60	4.00	240	4	80	320
Swine	53,000[e]	66.30[e]	53	13.26	703	4	265	968
Chickens	8,000,000[e]	2.50[e]	6000	0.40	2,400	500	1,250	3,650
Turkeys	280,000[e]	10[f]	280	2.00	560	25	250	810
Sheep	11,000[e]	82.40[e]	11	16.48	181	1	82	263
Total	8,582,000				21,599			30,782

[a] Based on a 0.1% illness rate (see text).

[b] Based on each animal illness costing 20% of total production value of that animal.

[c] Based on a 0.008% mortality rate (see text).

[d] FAO (1986).

[e] USDA (1989a).

[f] USCB (1990).

[g] Estimated.

Source: Pimentel, D., *Environment, Development and Sustainability*, 7, 229–252, 2005. With permission of Springer Science and Business Media.

might be little cost to the animal industry because the meat and other products are sometimes *sold and consumed by the public* before the test results are available. For example, about 3% of the chicken with illegal pesticide residues are sold in the market (NAS, 1987).

In addition to animal carcasses, pesticide-contaminated milk cannot be sold and must be disposed of. In some instances, these losses are substantial. For example, in Oahu, Hawaii, in 1982, 80% of the milk supply, worth more than $8.5 million, was condemned by the public health officials because it had been contaminated with the insecticide heptachlor (Baker et al., 2003). This incident had immediate and far-reaching effects on the entire milk industry on the island.

DESTRUCTION OF BENEFICIAL NATURAL PREDATORS AND PARASITES

In both natural and agricultural ecosystems, many species, especially predators and parasites, control or help control plant feeding arthropod populations. Indeed, these natural beneficial species make it possible for ecosystems to remain "green." With the parasites and predators keeping plant feeding populations at low levels, only a relatively small amount of plant biomass is removed each growing season by arthropods (Hairston et al., 1960; Pimentel, 1988).

Like pest populations, beneficial natural enemies and biodiversity (predators and parasites) are adversely affected by pesticides (Pimentel et al., 1993a). For example, the following pests have reached outbreak levels in cotton and apple crops after the natural enemies were destroyed by pesticides: cotton = cotton bollworm, tobacco budworm, cotton aphid, spider mites, and cotton loopers; apples = European red mite, red-banded leafroller, San Jose scale, oyster shell scale, rosy apple aphid, wooly apple aphid, white apple aphid, two-spotted spider mite, and apple rust mite. Major pest outbreaks have also occurred in other crops. Also, because parasitic and predaceous insects often have complex searching and attack behaviors, sub-lethal insecticide dosages may alter this behavior and in this way disrupt effective biological controls.

Fungicides also can contribute to pest outbreaks when they reduce fungal pathogens that are naturally parasitic on many insects. For example, the use of benomyl reduces populations of entomopathogenic fungi, resulting in increased survival of velvet bean caterpillars and cabbage loopers in soybeans. This eventually leads to reduced soybean yields.

When outbreaks of secondary pests occur because their natural enemies are destroyed by pesticides, additional and sometimes more expensive pesticide treatments have to be made in efforts to sustain crop yields. This raises the overall costs and contributes to pesticide-related problems.

An estimated $520 million can be attributed to costs of additional pesticide application and increased crop losses, both of which follow the destruction of natural enemies by various pesticides applied to crops (Table 13.3).

As in the United States, natural enemies are being adversely affected by pesticides worldwide. Although no reliable estimate is available concerning the impact of this in terms of increased pesticide use and reduced crop yields, general observations by entomologists indicate that the impact of loss of natural enemies is

TABLE 13.3

Losses Due to the Destruction of Beneficial Natural Enemies in U.S. Crops ($ millions)

Crops	Total Expenditures for Insect Control with Pesticides[a] ($)	Amount of Added Control Costs ($)
Cotton	320	160
Tobacco	5	1
Potatoes	31	8
Peanuts	18	2
Tomatoes	11	2
Onions	1	0.2
Apples	43	11
Cherries	2	1
Peaches	12	2
Grapes	1	3
Oranges	8	2
Grapefruit	5	1
Lemons	1	0.2
Nuts	160	16
Other	500	50
Total	1120	257.4 (520)[b]

[a] Pimentel et al. (1991).

[b] Because the added pesticide treatments do not provide as effective control as the natural enemies, we estimate that at least an additional $260 million in crops are lost to pests. Thus the total loss due to the destruction of natural enemies is estimated to be at least $520 million per year.

Source: Pimentel, D., *Environment, Development and Sustainability*, 7, 229–252, 2005. With permission of Springer Science and Business Media.

severe where pesticides are heavily used in many parts of the world. For example, from 1980 to 1985 insecticide use in rice production in Indonesia increased drastically (Oka, 1991). This caused the destruction of beneficial natural enemies of the brown planthopper and this pest population exploded. Rice yield decreased to the extent that rice had to be imported into Indonesia. The estimated cost of rice loss in just a 2-year period was $1.5 billion (FAO, 1988).

After this incident, Dr. I.N. Oka, who had previously developed a successful low-insecticide program for rice pests in Indonesia, was consulted by the Indonesian President Suharto's staff to determine what should be done to rectify the situation. Oka's advice was to substantially reduce insecticide use and return to a sound "treat-when-necessary" program that protected the natural enemies. Following Oka's advice, President Suharto mandated in 1986 on television that 57 of 64 pesticides would be withdrawn from use on rice and sound pest management practices implemented. Pesticide subsidies were also reduced to zero. By 1991, pesticide applications had been reduced by 65% and rice yields increased 12%.

Dr. Rosen (Hebrew University of Jerusalem, personal communication, 1991) estimates that natural enemies account for up to 90% of the control of pests species in agroecosystems. I estimate that at least 50% of the control of pest species is due to natural enemies. Pesticides provide an additional control, while the remaining 40% is due to host-plant resistance in agroecosystems (Pimentel, 1988).

Parasites, predators and host-plant resistance are estimated to account for about 80% of the nonchemical control of pest arthropods and plant pathogens in crops (Pimentel et al., 1991). Many cultural controls, such as crop rotations, soil and water management, fertilizer management, planting time, crop-plant density, trap crops, polyculture, and others, provide additional pest control. Together, these nonpesticide controls can be used to effectively reduce U.S. pesticide use by more than 50% without any reduction in crop yields or cosmetic standards (Pimentel et al., 1993a).

PESTICIDE RESISTANCE IN PESTS

In addition to destroying natural enemy populations, the extensive use of pesticides has often resulted in the development and evolution of pesticide resistance in insect pests, plant pathogens, and weeds. An early report by the United Nations Environmental Program (UNEP, 1979) suggested that pesticide resistance ranked as one of the top four environmental problems of the world. About 520 insect and mite species, a total of nearly 150 plant pathogen species, and about 273 weeds species are now resistant to pesticides (Stuart, 2003).

Increased pesticide resistance in pest populations frequently results in the need for several additional applications of the commonly used pesticides to maintain crop yields. These additional pesticide applications compound the problem by increasing environmental selection for resistance. Despite efforts to deal with the pesticide resistance problem, it continues to increase and spread to other species. A striking example of pesticide resistance occurred in northeastern Mexico and the Lower Rio Grande of Texas (NAS, 1975). Over time extremely high pesticide resistance had developed in the tobacco budworm population on cotton. Finally approximately 285,000 ha of cotton had to be abandoned, because the insecticides were totally ineffective because of the extreme resistance in the budworm. The economic and social impact on these Texan and Mexican farmers dependent on cotton was devastating.

The study by Carrasco-Tauber (1989) indicates the extent of costs associated with pesticide resistance. They reported a yearly loss of $45–$120 per hectare to pesticide resistance in California cotton. A total of 4.2 million ha of cotton were harvested in 1984; thus, assuming a loss of $82.50 per hectare, approximately $348 million of the California cotton crop was lost to resistance. Since $3.6 billion of U.S. cotton was harvested in 1984 (USCB, 1990), the loss due to resistance for that year was approximately 10%. Assuming a 10% loss in other major crops that receive heavy pesticide treatments in the United States, crop losses due to pesticide resistance are estimated to be about $1.5 billion per year.

Furthermore, efforts to control resistant *Heliothus* spp. (corn ear worm) exact a cost on other crops when large, uncontrolled populations of *Heliothus* and other pests disperse onto other crops. In addition, the cotton aphid and the whitefly exploded as secondary cotton pests because of their resistance and their natural enemies' exposure to high concentrations of insecticides.

The total external cost attributed to the development of pesticide resistance is estimated to range between 10% and 25% of current pesticide treatment costs (Harper and Zilberman, 1990), or more than $1.5 billion each year in the United States. In other words, at least 10% of pesticide used in the United States is applied just to combat increased resistance that has developed in several pest species.

Although the costs of pesticide resistance are high in the United States, the costs in tropical developing countries are significantly greater, because pesticides are not only used to control agricultural pests, but are also vital for the control of arthropod disease vectors. One of the major costs of resistance in tropical countries is associated with malaria control. By 1985, the incidence of malaria in India after early pesticide use declined to about 2 million cases from a peak of 70 million cases. However, because mosquitoes developed resistance to pesticides, as did malarial parasites to drugs, the incidence of malaria in India has now exploded to about 60 million cases per year (Malaria, 2000). Problems are occurring not only in India but also in the rest of Asia, Africa, and South America. The total number of malaria cases in the world is now 2.5 billion (McMichael, 2001).

HONEYBEE AND WILD BEE POISONINGS AND REDUCED POLLINATION

Honeybees and wild bees are vital for the pollination of fruits, vegetable, and other crops. Bees are essential to the production of about one-third of U.S. and world crops. Their benefits to U.S. agriculture are estimated to be about $40 billion per year (Pimentel et al., 1997). Because most insecticides used in agriculture are toxic to bees, pesticides have a major impact on both honeybee and wild bee populations. D. Mayer (Washington State University, personal communication, 1990) estimates that approximately 20% of all honeybee colonies are adversely affected by pesticides. He includes the approximately 5% of U.S. honeybee colonies that are killed outright or die during winter because of pesticide exposure. Mayer calculates that the direct annual loss reaches $13.3 million per year (Table 13.4). Another 15% of the honeybee colonies either are seriously weakened by pesticides or suffer losses when apiculturists have to move colonies to avoid pesticide damage.

TABLE 13.4
Estimated Honeybee Losses and Pollination Losses from Honeybees and Wild Bees

Colony losses from pesticides	$13.3 million/year
Honey and wax losses	$25.3 million/year
Loss of potential honey production	$27.0 million/year
Bee rental for pollination	$8.0 million/year
Pollination losses	$210.0 million/year
Total	$283.6 million/year

Source: Pimentel, D., *Environment, Development and Sustainability*, 7, 229–252, 2005. With permission of Springer Science and Business Media.

According to Mayer, the yearly estimated loss from partial honeybee kills, reduced honey production, plus the cost of moving colonies totals about $25.3 million per year. Also, as a result of heavy pesticide use on certain crops, beekeepers are excluded from 4 to 6 million ha of otherwise suitable apiary locations, according to Mayer. He estimates the yearly loss in potential honey production in these regions is about $27 million each year (Table 13.4).

In addition to these direct losses caused by the damage to honeybees and honey production, many crops are lost because of the lack of pollination. In California, for example, approximately 1 million colonies of honeybees are rented annually at $55 per colony to augment the natural pollination of almonds, alfalfa, melons, and other fruits and vegetables (Burgett, 2000). Since California produces nearly half of our bee-pollinated crops, the total cost for honeybee rental for the entire country is estimated at $40 million per year. Of this cost, I estimate that at least one-tenth or $4 million is attributed to the effects of pesticides (Table 13.4).

Estimates of annual agricultural losses due to the reduction in pollination caused by pesticides may be as high as $4 billion per year (J. Lockwood, University of Wyoming, personal communication, 1990). For most crops, both yield and quality are enhanced by effective pollination. Several investigators have demonstrated that for various cotton varieties, effective pollination by honeybees resulted in yield increases from 20% to 30%.

Mussen (1990) emphasizes that poor pollination will not only reduce crop yields, but equally important, it will reduce the quality of some crops, such as melon and fruits. In experiments with melons, E.L. Atkins (University of California [Davis], personal communication, 1990) reported that with adequate pollination melon yields increased 10% and melon quality was raised 25% as measured by the dollar value of the melon crop.

Based on the analysis of honeybee and related pollination losses from wild bees caused by pesticides, pollination losses attributed to pesticides are estimated to represent about 10% of pollinated crops and have a yearly cost of about $210 million per year (Table 13.4). Clearly, the available evidence confirms that the yearly cost of direct honeybee losses, together with reduced yields resulting from poor pollination, is significant.

CROP AND CROP PRODUCT LOSSES

Basically, pesticides are applied to protect crops from pests to increase yields, but sometimes the crops are damaged by the pesticide treatments. This occurs when (1) the recommended dosages suppress crop growth, development, and yield; (2) pesticides drift from the targeted crop to damage adjacent crops; (3) residual herbicides either prevent chemical-sensitive crops from being planted; and (4) excessive pesticide residue accumulates on crops, necessitating the destruction of the harvest. Crop losses translate into financial losses for growers, distributors, wholesalers, transporters, retailers, food processors, and others. Potential profits as well as investments are lost. The costs of crop losses increase when the related costs of investigations, regulation, insurance, and litigation are added to the equation. Ultimately the consumer pays for these losses in higher marketplace prices.

Data on crop losses due to pesticides are difficult to obtain. Many losses are never reported to the state and federal agencies because the parties settle privately (Pimentel et al., 1993a).

Damage to crops may occur even when recommended dosages of herbicides and insecticides are applied to crops under normal environmental conditions. Recommended dosages of insecticides used on crops have been reported to suppress growth and yield in both cotton and strawberry crops (ICAITI, 1977; Reddy et al., 1987; Trumbel et al., 1988). The increase in susceptibility of some crops to insects and diseases following normal use of 2,4-D and other herbicides has been demonstrated (Oka and Pimentel, 1976; Pimentel, 1994). Furthermore, when weather or soil conditions are inappropriate for pesticide application, herbicide treatments may cause yield reductions ranging from 2% to 50% (Pimentel et al., 1993a).

Crops are lost when pesticides drift from the target crops to nontarget crops located as much as several miles downwind (Barnes et al., 1987). Drift occurs with most methods of pesticide application including both ground and aerial equipment; the potential problem is greatest when pesticides are applied by aircraft. With aircraft, from 50% to 75% of the pesticide applied never reaches the target acre (Akesson and Yates, 1984; Mazariegos, 1985; Pimentel, et al., 1993a). In contrast, 10%–35% of the pesticide applied with ground application equipment misses the target area (Hall, 1991). The most serious drift problems are caused by "speed sprayers" and ultralow volume (ULV) equipment, because relatively concentrated pesticide is applied. The concentrated pesticide has to be broken into small droplets to achieve adequate coverage.

Crop injury and subsequent loss due to drift are particularly common in areas planted with diverse crops. For example, in southwest Texas in 1983 and 1984, nearly $20 million in cotton was destroyed from drifting 2,4-D herbicide when adjacent wheat fields were aerially sprayed with the herbicide (Hanner, 1984). Because of the drift problem, most commercial applicators carry insurance that costs about $245 million per year (Pimentel et al., 1993a; Table 13.5).

TABLE 13.5
Estimated Loss of Crops and Trees Due to the Use of Pesticides

Impacts	Total Costs (in millions of dollars)
Crop losses	136
Crop applicator insurance	245
Crops destroyed because of excess pesticide contamination	1000
Governmental investigations and testing	10
Total	1391

Source: Pimentel, D., *Environment, Development and Sustainability*, 7, 229–252, 2005. With permission of Springer Science and Business Media.

When residues of some herbicides persist in the soil, crops planted in rotation are sometimes injured. This has happened with a corn and soybean rotation. When atrazine or Sceptor herbicides were used in corn, the soybean crop planted after was seriously damaged by the herbicides that persist in the soil. This problem also has environmental problems associated. For example, if the herbicide treatment prevents another crop from being grown, soil erosion may be intensified (Pimentel et al., 1993a).

An average 0.1% loss in annual U.S. production of corn, soybeans, cotton, and wheat, which together account for about 90% of the herbicides and insecticides used in U.S. agriculture, was valued at $35.3 million in 1987 (NAS, 1989). Assuming that only one-third of the incidents involving crop losses due to pesticides are reported to authorities, the total value of all crop lost because of pesticides could be as high as 3 times this amount or $106 million annually.

However, this $106 million does not take into account other crop losses, nor does it include major events such as the large-scale losses that have occurred in one season in Iowa ($25–$30 million), in Texas ($20 million), and in California's aldicarb/watermelon crisis ($8 million) (Pimentel et al., 1993a). These recurrent losses alone represent an average of $30 million per year, raising the estimated average crop loss value from the use of pesticides to approximately $136 million each year.

Additional losses are incurred when food crops are disposed of because they exceed the FDA and EPA regulatory tolerances for pesticide residue levels. Assuming that all the crops and crop products that exceed the FDA and EPA regulatory tolerances (reported to be 1%–5%) were disposed of as required by law, then about $1 billion in crops would be destroyed because of excessive pesticide contamination.

Special investigations and testing for pesticide contamination are estimated to cost the nation more than $10 million each year (Pimentel et al., 1993a).

GROUND- AND SURFACE WATER CONTAMINATION

Certain pesticides applied at recommended dosages to crops eventually end up in ground- and surface waters. The three most common pesticides found in groundwater are aldicarb, alachlor, and atrazine (Cornell, 2003). Estimates are that nearly one-half of the groundwater and well water in the United States is or has the potential to be contaminated (Holmes et al., 1988; USGS, 1996). EPA (1990) reported that 10% of community wells and 4% of rural domestic wells have detectable levels of at least one pesticide of the 127 pesticides tested in a national survey. Estimated costs to sample and monitor well and groundwater for pesticide residues costs $1100 per well per year (USGS, 1995). With 16 million wells in the United States, the cost of monitoring all the wells for pesticides would cost $17.7 billion per year (Well-Owner, 2003).

Two major concerns about groundwater contamination with pesticides are that about one-half the human population obtains its water from wells and once groundwater is contaminated, the pesticide residues remain for long periods of time. Not only are there extremely few microbes present in groundwater to degrade the pesticides, but the groundwater recharge rate is less than 1% per year (CEQ, 1980).

Monitoring pesticides in groundwater is only a portion of the total cost of groundwater contamination. There is also the high cost of cleanup. For instance, at the Rocky Mountain Arsenal near Denver, Colorado, the removal of pesticides from the groundwater and soil was estimated to cost approximately $2 billion. If all pesticide-contaminated groundwater were to be cleared of pesticides before human consumption, the cost would be about $500 million per year. Note the cleanup process requires a water survey to target the contaminated water for cleanup. Thus, adding the monitoring and cleaning costs, the total cost incurred for cleansing the pesticide-polluted groundwater is estimated to be about $2 billion annually. The $17.7 billion figure shows how impossible it would be to expect the public to pay for pesticide-free well water.

FISHERY LOSSES

Pesticides are washed into aquatic ecosystems by water runoff and soil erosion. About 13 t/ha/year are washed or blown from pesticide-treated cropland into adjacent locations including rivers and lakes (Unnevehr et al., 2003). Pesticides also can drift during application and contaminate aquatic systems. Some soluble pesticides are easily leached into streams and lakes.

Once in aquatic ecosystems, pesticides cause fishery losses in several ways. These include high pesticide concentrations in water that directly kill fish; low doses that may kill highly susceptible fish fry; or the elimination of essential fish foods, like insects and other invertebrates. In addition, because government safety restrictions ban the catching or sale of fish contaminated with pesticide residues, such fish are unmarketable and are an economic loss.

Only 6–14 million fish are reported killed by pesticides each year (Pimentel et al., 1993a). However, this is an underestimate because fish kills cannot be investigated quickly enough to determine accurately the cause of the kill. Also, if the fish are in fast-moving waters in rivers, the pesticides are diluted or the pesticides cannot be identified. Many fish sink to the bottom and cannot be counted.

The best estimate for the value of a fish is $10. This is based on EPA fining Coors Beer $10 per fish when Coors polluted a river (Barometer, 1991). Thus, the estimate of the value of fish killed each year is only $10–$24 million per year. This is an underestimate and I estimate $100 million per year minimum.

WILD BIRDS AND MAMMALS

Wild birds and mammals are damaged and destroyed by pesticides and these animals make excellent "indicator species." Deleterious effects on wildlife include death from direct exposure to pesticides or secondary poisonings from consuming contaminated food; reduced survival, growth, and reproductive rates from exposure to sublethal dosages; and habitat reduction through the elimination of food resources and refuges. In the United States, approximately 3 kg of pesticide is applied per hectare on about 160 million ha of cropland each year (Pimentel et al., 1993a). With such heavy dosages of pesticides applied, it is expected that wildlife would be significantly impacted.

The full extent of bird and mammal kills is difficult to determine because birds and mammals are often secretive, camouflaged, highly mobile, and live in dense grass, shrubs, and trees. Typical field studies of the effects of pesticides often obtain extremely low estimates of bird and mammal mortality (Mineau et al., 1999). This is because bird and small mammal carcasses disappear quickly, well before the dead birds and small mammals can be found and counted. Even when known numbers of bird carcasses were placed in identified locations in the field, from 62% to 92% of the animals disappeared overnight due to vertebrate and invertebrate scavengers (Balcomb, 1986). Then in addition, field studies seldom account for birds that die a distance from the treated areas. Finally, birds often hide and die in inconspicuous locations.

Nevertheless, many bird kills caused by pesticides have been reported. For instance, 1200 Canada Geese were killed in one wheat field that was sprayed with a 2:1 mixture of parathion and methyl parathion at a rate of 0.8 kg/ha (White et al., 1982). Carbofuran applied to alfalfa killed more than 5000 ducks and geese in five incidents, while the same chemical applied to vegetable crops killed 1400 ducks in a single application (Flickinger et al., 1980, 1991). Carbofuran is estimated to kill 1 to 2 million birds each year (EPA, 1989). Another pesticide, diazinon, applied to three golf courses killed 700 Atlantic brant geese of the wintering population of just 2500 birds (Stone and Gradoni, 1985).

EPA reports that there are 1100 documented cases of bird kills each year in the United States (ABCBirds, 2003). Birds are not only killed in the United States but are also killed as they migrate from North America to South America. For example, more than 4000 carcasses of Swainson's hawks were reported poisoned by pesticides in late 1995 and early 1996 in farm fields of Argentina (CWS, 2003). Although it was not possible to know the total kill, a conservative estimate made it out to be more than 20,000 hawks.

Several studies report that the use of some herbicides has a negative impact on some young birds. As the weeds would have harbored some insects in the crops, their nearly total elimination by herbicides is devastating to particular bird populations (Potts, 1986; R. Beiswenger, University of Wyoming, personal communication, 1990). This has led to significant reductions in the grey partridge in the United Kingdom and in the common pheasant in the United States. In the case of the partridge, population levels have decreased more than 77% because the partridge chicks (also pheasant chicks) depend on insects to supply them with the needed protein for their development and survival.

Frequently, the form (e.g., granules on spray) of a pesticide influences its toxicity to wildlife (Hardy, 1990). For example, treated seed and insecticide granules, including carbofuran, fensulfothion, fonofos, and phorate, are particularly toxic to birds. Estimates are that from 0.23 to 1.5 birds per hectare were killed in Canada, while in the United States the estimates of kill ranged from 0.25 to 8.9 birds killed per hectare per year by the pesticides (Mineau, 1988).

Pesticides also adversely affect the reproductive potential of many birds and mammals. Exposure of birds, especially predatory birds, to chlorinated insecticides has caused reproductive failure, sometimes attributed to eggshell thinning (Elliot et al., 1988). Most of the affected predatory birds, like the bald eagle and peregrine falcon, have recovered since the banning of dichlorodiphenyltrichloroethane (DDT) and most other chlorinated insecticides in the United States (Unnevehr et al., 2003). Although the United States and most other developed countries have banned DDT and other chlorinated insecticides, other countries, such as India and China, are still producing, exporting, and using DDT (Asia Times, 2001).

Habitat alteration and destruction can be expected to reduce mammal and bird populations. For example, when glyphosphate (Roundup) was applied to forest clear cuts to eliminate low-growing vegetation, like shrubs and small trees, the southern red-backed vole population was greatly reduced because its food source and cover were practically eliminated (D'Anieri et al., 1987). Similar effects from herbicides have been reported on other mammals. Overall, the impacts of pesticides on mammal populations have been inadequately investigated.

Although the gross values for wildlife are not available, expenditures involving wildlife made by humans are one measure of the monetary value. Nonconsumptive users of wildlife spent an estimated $14.3 billion on their sport (USFWS, 1988). Yearly, U.S. bird watchers spend an estimated $600 million on their sport and an additional $500 million on birdseed, or a total of $1.1 billion (USFWS, 1988). For bird watching, the estimated cost is about 40¢ per bird. The money spent by hunters to harvest 5 million game birds was $1.1 billion, or approximately $216 per bird (USFWS, 1988). In addition, the estimated cost of replacing a bird of an affected species to the wild, as in the case of the Exxon Valdez oil spill, was $800 per bird (Dobbins, 1986).

If it is assumed that the damages that pesticides inflict on birds occur primarily on the 160 million ha of cropland that receive the most pesticide, and the bird population is estimated to be 4.4 birds per hectare of cropland (Boutin et al., 1999), then 720 million birds are directly exposed to pesticides. Also, if it is conservatively estimated that only 10% of the bird population is killed by the pesticide treatments, it follows that the total number of birds killed is 72 million birds. Note this estimate is at the lower end of the range of 0.25–8.9 birds killed per hectare per year mentioned earlier.

The American bald eagle and other predatory birds suffered high mortalities because of DDT and other chlorinated insecticides. The bald eagle population declined primarily because of pesticides and was placed on the endangered species list. After DDT and the other chlorinated insecticides were banned in 1972, it took nearly 30 years for the bird populations to recover. The American bald eagle was recently removed from the endangered species list (Millar, 1995).

I assumed a value of a bird to be about $30 based on the information presented, plus the fact that the cost of a fish is about $10, even an 1-in. fish. Thus, the total economic impact of pesticides on birds is estimated to be $2.1 billion per year. This estimate does not include the birds killed due to the death of one of the parents and in turn the deaths of the nestlings. It also does not include nestlings killed because they were fed contaminated arthropods and other foods.

MICROBES AND INVERTEBRATES

Pesticides easily find their way into soils, where they may be toxic to arthropods, earthworms, fungi, bacteria, and protozoa. Small organisms are vital to ecosystems because they dominate both the structure and function of ecosystems (Pimentel et al., 1992).

For example, an estimated 4.5 tons per hectare of fungi and bacteria exist in the upper 15 cm of soil. They, with the arthropods, make up 95% of all species and 98% of the biomass (excluding vascular plants). The microbes are essential to proper functioning in the ecosystem, because they break down organic matter, enabling the vital chemical elements to be recycled (Atlas and Bartha, 1987; Pimentel et al., 1997). Equally important is their ability to "fix" nitrogen, making it available to plants and ecosystems (Pimentel et al., 1997).

Earthworms and insects aid in bringing new soil to the surface at a rate of up to 200 tons/ha/year (Pimentel et al., 1993a). This action improves soil formation and structure for plant growth and makes various nutrients more available for absorption by plants. The holes (up to 10,000 holes per square meter) in the soil made by earthworms and insects also facilitate the percolation of water into the soil (Edwards and Lofty, 1982).

Insecticides, fungicides, and herbicides reduce species diversity in the soil as well as the total biomass of this biota. Stringer and Lyons (1974) reported that where earthworms had been killed by pesticides, the leaves of apple trees accumulated on the surface of the soil and increased the incidence of scab in the orchards. Apple scab, a disease carried over from season to season on fallen leaves, is commonly treated with fungicides. Some fungicides, insecticides, and herbicides are toxic to earthworms, which would otherwise remove and recycle the fallen leaves.

On golf courses and other lawns, the destruction of earthworms by pesticides results in the accumulation of dead grass or thatch in the turf (Potter and Braman, 1991). To remove this thatch special equipment must be used and it is expensive.

Although these microbes and invertebrates are essential to the vital structure and function of both natural and agricultural ecosystems, it is impossible to place a money value on the damage caused by pesticides to this large group of organisms. To date, no relevant quantitative data on the value of microbe and invertebrate destruction by pesticides are available.

GOVERNMENT FUNDS FOR PESTICIDE POLLUTION CONTROL

A major environmental cost associated with all pesticide use is the cost of carrying out state and federal regulatory actions, as well as pesticide-monitoring programs needed to control pesticide pollution. Specifically, these funds are spent to reduce the hazards of pesticides and to protect the integrity of the environment and public health.

About $10 million is spent each year by state and federal governments to train and register pesticide applicators. Also, more than $60 million is spent each year by the EPA to register and re-register pesticides. In addition, about $400 million is spent to monitor pesticide contamination of fruits, vegetables, grains, meat, milk, water, and other items for pesticide contamination. Thus, at least $470 million is invested by state and federal governmental organizations.

Although enormous amounts of government funds are being spent to reduce pesticide pollution, many costs of pesticides are not taken into account. Also, many serious environmental and social problems remain to be corrected by improved government policies.

ETHICAL AND MORAL ISSUES

Although pesticides provide about $40 billion per year in saved U.S. crops, the data of this analysis suggest that the environmental and social costs of pesticides to the nation total approximately $10 billion. From a strictly cost/benefit approach, it appears that pesticide use is beneficial. However, the nature of the environmental and public health costs of pesticides has other trade-offs involving environmental quality and public health.

One of these issues concerns the importance of public health vs. pest control. For example, assuming that pesticide-induced cancers number more than 10,000 cases per year and that pesticides return a net agricultural benefit of $32 billion per year, each case of cancer is "worth" $3.2 million in pest control. In other words, for every $3.2 million in pesticide benefits, one person falls victim to cancer. Social mechanisms and market economics provide these ratios, but they ignore basic ethics and values.

In addition, pesticide pollution of the global environment raises numerous other ethical questions. The environmental insult of pesticides has the potential to demonstrably disrupt entire ecosystems. All through history, humans have felt justified in removing forests, draining wetlands, and constructing highways and housing in various habitats. White (1967) has blamed the environmental crisis on religious teachings of mastery over nature. Whatever the origin, pesticides exemplify this attempt at mastery, and even a noneconomic analysis would question its justification. There is a clear need for a careful and comprehensive assessment of the environmental impacts of pesticides on agriculture and natural ecosystems.

In addition to the ethical status of ecological concerns are questions of economic distribution of costs. Although farmers spend about $10 billion per year for pesticides, little of the pollution costs that result are borne by them or the pesticide-producing chemical companies. Rather, most of the costs are borne off-site by public illnesses and environmental destruction. Standards of social justice suggest that a more equitable allocation of responsibility is desirable.

These ethical issues do not have easy answers. Strong arguments can be made to support pesticide use based on social and economic benefits. However, evidence of these benefits should not cover up the public health and environmental problems. One goal should be to maximize the benefits while at the same time minimizing the health, environmental, and social costs. A recent investigation pointed out that U.S. pesticide use could be reduced by one-half without any reduction in crop yields (Pimentel et al., 1993b). The judicious use of pesticides could reduce the environmental and social costs, while it benefits farmers economically in the short-term and supports sustainability of agriculture in the long-term.

Public concern over pesticide pollution confirms a national trend toward environmental values. Media emphasis on the issues and problems caused by pesticides has contributed to a heightened public awareness of ecological concerns. This awareness is encouraging research in sustainable agriculture and in nonchemical pest management.

Granted, substituting nonchemical pest controls in U.S. agriculture would be a major undertaking and would not be without its costs. The direct and indirect benefits and costs of implementation of a policy to reduce pesticide use should be researched in detail. Ideally, such a program should both enhance social equitability and promote public understanding of how to better protect public health and the environment, while abundant, safe food is supplied. Clearly, it is essential that the environmental and social costs and benefits of pesticide use be considered when future pest control programs are being considered and developed. Such costs and benefits should be given ethical and moral scrutiny before policies are implemented, so that sound, sustainable pest management practices are available to benefit farmers, society, and the environment.

CONCLUSION

An investment of about $10 billion in pesticide control each year saves approximately $40 billion in U.S. crops, based on direct costs and benefits. However, the indirect costs of pesticide use to the environment and public health need to be balanced against these benefits. Based on the available data, the environmental and public health costs of recommended pesticide use total more than $9 billion each year (Table 13.6). Users of pesticides pay directly only about $3 billion, which includes problems arising from pesticide resistance and destruction of natural enemies. Society eventually pays this $3 billion plus the remaining $9 billion in environmental and public health costs (Table 13.6).

Our assessment of the environmental and health problems associated with pesticides was made more difficult by the complexity of the issues and the scarcity of data. For example, what is an acceptable monetary value for a human life lost or a cancer illness due to pesticides? Equally difficult is placing a monetary value on killed wild birds and other wildlife; on the dearth of invertebrates, or microbes lost; or on the price of contaminated food and groundwater.

TABLE 13.6
Total Estimated Environmental and Social Costs from Pesticide Use in the United States

Costs	Millions of $/year
Public health impacts	1140
Domestic animals deaths and contaminations	30
Loss of natural enemies	520
Cost of pesticide resistance	1500
Honeybee and pollination losses	334
Crop losses	1391
Fishery losses	100
Bird losses	2160
Groundwater contamination	2000
Government regulations to prevent damage	470
Total	9645

Source: Pimentel, D., *Environment, Development and Sustainability*, 7, 229–252, 2005. With permission of Springer Science and Business Media.

In addition to the costs that cannot be accurately measured, there are many costs that were not included in the $12 billion figure. If the full environmental, public health and social costs could be measured as a whole, the total cost might be nearly double the $12 billion figure. Such a complete and long-term cost/benefit analysis of pesticide use would reduce the perceived profitability of pesticides.

The efforts of many scientists to devise ways to reduce pesticide use in crop production while still maintaining crop yields have helped but a great deal more needs to be done. Sweden, for example, has reduced pesticide use by 68% without reducing crop yields or the cosmetic standards (PCC, 2002). At the same time, public pesticide poisonings have been reduced 77%. It would be helpful if the United States adopted a similar goal to that of Sweden. Unfortunately with some groups in the United States, integrated pest management (IPM) is being used as a means of justifying pesticide use.

REFERENCES

ABCBirds. 2003. Pesticides and Birds Campaign, http://www.abcbirds.org/pesticides/pesticideindex.htm (February 3, 2003).

Akesson, N.B. and W.E. Yates. 1984. Physical parameters affecting aircraft spray application. In W.Y. Garner and J. Harvey (eds.), *Chemical and Biological Controls in Forestry*, pp. 95–111. Washington, D.C.: American Chemical Society.

Asia Times. 2001. India/Pakistan. http://www.atimes.com/ind-pak/CF14Df01.html (February 3, 2003).

Atlas, R.M. and R. Bartha. 1987. *Microbial Biology: Fundamentals and Applications*. 2nd ed. Menlo Park, CA: Benjamin Cummings Co.

Baker, B.P., C.M. Benbrook, G. Groth, et al. 2003. Summary: Pesticide residues in conventional, IPM-grown and organic foods: Insights from three U.S. data sets. http://www.consumersunion.org/pub/core_food_safety/002312.html (January 19, 2003).

Balcomb, R. 1986. Songbird carcasses disappear rapidly from agricultural fields. *Auk* 103: 817–821.

Barometer. 1991. Too much beer kills thousands. *Oregon State University Barometer*, 14 May.

Barnes, C.J., T.L. Lavy, and J.D. Mattice. 1987. Exposure of non-applicator personnel and adjacent areas to aerially applied propanil. *Bulletin of Environmental Contamination and Toxicology* 39: 126–133.

Boutin, C., K.E. Freemark, and D.E. Kirdk. 1999. Spatial and temporal patterns of bird use of farmland in southern Ontario. *Canadian Field Naturalist* 113(3): 430–460.

Burgett, M. 2000. Pacific Northwest Honey Bee Pollination Survey. http://www.nhb/org.download/2000polin.pdf (January 20, 2003).

Carlsen, E.A., A. Giwercman, N. Kielding, et al. 1992. Evidence for decreasing quality of semen during the past 15 years. *British Medical Journal* 305: 609–613.

Carrasco-Tauber, C. 1989. Pesticide Productivity Revisited. M.S. Thesis, Amherst, MA: University of Massachusetts.

CEQ. 1980. *The Global 2000 Report to the President of the U.S. Entering the 21st Century*. New York: Pergamon Press.

Colburn, T., J.P. Myers, and D. Dumanoski. 1996. *Our Stolen Future: How We Are Threatening Our Fertility, Intelligence, and Survival: A Scientific Detective Story*. New York: Dutton.

Cornell. 2003. Common Pesticides in Groundwater. http://pmep.cce.cornell.edu/facts-slides-self/slide-set/gwater09.html (January 21, 2003).

CWS. 2003. Pesticides and Wild Birds. Canadian Wildlife Service. http://www.cws-scf.ec.gc.ca/hww-fap/hww-fap.cfm?ID_species-90&lang=e (February 3, 2003).

D'Anieri, P., D.M. Leslie, and M.L. McCormack. 1987. Small mammals in glyphosate-treated clearcuts in Northern Maine. *Canadian Field Naturalist* 101: 547–550.

Dobbins, J. 1986. Resources Damage Assessment of the T/V Puerto-Rican Oil Spill Incident. James Dobbins Report to NOAA, Sanctuary Program Division, Washington, D.C.

Edwards, C.A. and J.R. Lofty. 1982. Nitrogenous fertilizers and earthworm populations in agricultural soils. *Soil Biology and Biochemistry* 14: 515–521.

Elliot, J.E., R.J. Norstrom, and J.A. Keith. 1988. Organochlorines and eggshell thinning in Northern Gannets (*Sula bassanus*) from Eastern Canada 1968–1984. *Environmental Pollution* 52: 81–102.

EPA. 1977. Minutes of Administrator's Pesticide Policy Advisory Committee, March. Washington, D.C.: US Environmental Protection Agency.

EPA. 1989. Carbofuran: A Special Review Technical Support Document. Office of Pesticides and Toxic Substances. Washington, D.C.: US Environmental Protection Agency.

EPA. 1990. *National Pesticide Survey-Summary*. Washington, D.C.: US Environmental Protection Agency.

EPA. 1992. Hired Farm Workers Health and Well-Being at Risk. United States General Accounting Office Report to Congressional Requesters. February.

FAO. 1988. Integrated Pest Management in Rice in Indonesia. Jakarta: Food and Agriculture Organization, United Nations. May.

Flickinger, E.L., K.A. King, W.F. Stout, et al. 1980. Wildlife hazards from furadan 3G applications to rice in Texas. *Journal of Wildlife Management* 44: 190–197.

Flickinger, E.L., G. Juenger, T.J. Roffe, et al. 1991. Poisoning Canada geese in Texas by parathion sprayed for control of Russian wheat aphid. *Journal of WildLife Diseases* 27: 265–268.

Groth, E., C.M. Benbrook, and K. Lutx. 1999. Do You Know What You're Eating? An Analysis of U.S. Government Data on Pesticide Residues in Foods. http://www/consumers union.org/food/do_you_know2.htm (January 19, 2003).

Hairston, N.G., F.E. Smith, and L.B. Slobodkin. 1960. Community structure, population control and competition. *American Naturalist* 94: 421–425.

Hall, F.R. 1991. Pesticide application technology and integrated pest management (IPM). In D. Pimentel (ed.), *Handbook of Pest Management in Agriculture*, Vol. II, pp. 135–170. Boca Raton, FL: CRC Press.

Hanner, D. 1984. Herbicide drift prompts state inquiry. *Dallas Morning News*, July 25.

Hardy, A.R. 1990. Estimating exposure: The identification of species at risk and routes of exposure. In L. Somerville and C.H. Walker (eds.), *Pesticide Effects on Terrestrial Wildlife*, pp. 81–97. London: Taylor & Francis.

Harper, C.R. and D. Zilberman. 1990. Pesticide regulation: Problems in trading off economic benefits against health risks. In D. Zilberman and J.B. Siebert (eds.), *Economic Perspectives on Pesticide Use in California*, pp. 181–208. Berkeley, CA: University of California.

Hart, K. and D. Pimentel. 2002. Public health and costs of pesticides. In D. Pimentel (ed.), *Encyclopedia of Pest Management*, pp. 677–679. New York: Marcel Dekker.

Hebert, H.J. 2003. EPA guidelines address kids, cancer risks. Detroit Free Press. http://www.freep.com/news/childrenfirst/risk4_20030304.htm (March 10, 2003).

Holmes, T., E. Neilsen, and L. Lee. 1988. *Managing Groundwater Contamination in Rural Areas: Rural Development Perspectives.* Washington, D.C.: US Department of Agriculture, Economic Research Series.

ICAITI. 1977. An Environmental and Economic Study of the Consequence of Pesticide Use in Central American Cotton Production. Guatemala City, Guatemala: Final Report, Central American Research Institute for Industry, United Nations Environment Program.

Kaiser, J. 2003. Economics: How much are human lives and health worth? www.rff.org/rff/News/Coverage/2003/March/How-Much-Are-Human-Lives-and-Health-Worth.cfm-72k (September 3, 2003).

Malaria. 2000. Malaria in India. http://www/brown.edu/Research/EnvStudies_Theses/full9900/creod/malaria_in_india.html (January 20, 2003).

Mazariegos, F. 1985. The use of pesticides in the cultivation of cotton in Central America. Guatemala, United Nations Environment Program, Industry and Environment. July/August/September.

McCarthy, S. 1993. Congress takes a look at estrogenic pesticides and breast cancer. *Journal of Pesticide Reform* 13(4): 25.

McMichael, A.J. 2001. *Human Frontiers, Environments and Disease: Pest Patterns, Uncertain Future*. Cambridge, UK: Cambridge University Press.

Millar, J.G. 1995. Fish and Wildlife Service's proposal to reclassify the bald eagle in most of the lower 48 states. *Journal of Raptor Research* 29(1): 71.

Mineau, P. 1988. Avian mortality in agroecosystems. I. The case against granule insecticides in Canada. In M.P. Greaves, B.D. Smith, and P.W. Greig-Smith (eds.), *Field Methods for the Environmental Effects of Pesticides*, pp. 3–12. British Crop Protection Council (BPCP) Monograph 40. London: Thornton Heath.

Mineau, P., M.R. Fletcher, L.C. Glaser, et al. 1999. Poisoning of raptors with organophosphorus and carbamate pesticides with emphasis on Canada, U.S., and U.K. *Journal of Raptor Research* 33(1): 1–37.

Mussen, E. 1990. California crop pollination. *Gleanings in Bee Culture* 118: 646–647.

NAS. 1975. *Pest Control: An Assessment of Present and Alternative Technologies*. 4 volumes. Washington, D.C.: National Academy of Sciences.

NAS. 1987. *Regulating Pesticides in Food*. Washington, D.C.: National Academy of Sciences.

NAS. 1989. *Alternative Agriculture*. Washington, D.C.: National Academy of Sciences.

National Animal Poison Control Centers. 2003. http://www.canismajor.com/dog/poison.html (January 19, 2003).

National Residue Program. 2002. http://www.fsis.usda.gov/OPHS/blue2002/-8k (February 3, 2003).

Oka, I.N. 1991. Success and challenges of the Indonesian national integrated pest management program in the rice based cropping system. *Crop Protection* 10: 163–165.

Oka, I.N. and D. Pimentel. 1976. Herbicide (2, 4-D) increases insect and pathogen pests on corn. *Science* 193: 239–240.

Pan-UK. 2003. Current Pesticide Spectrum, Global Use and Major Concerns. http://www.pan-uk.org/briefing/SIDA_Fil/Chap1.htm (January 18, 2003).

PCC. 2002. News Bites. http://www.pccnaturalmarkets.com/sc/0205/newsbites.html (January 19, 2003).

Pimentel, D. 1997. Pest management in agriculture. In D. Pimentel (ed.), *Techniques for Reducing Pesticide Use: Environmental and Economic Benefits*, pp. 1–11. Chichester, UK: John Wiley & Sons.

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

Pimentel, D. 1994. Insect population responses to environmental stress and pollutants. *Environmental Reviews* 2(1): 1–15.

Pimentel, D. and A. Greiner. 1997. Environmental and socio-economic costs of pesticide use. In D. Pimentel (ed.), *Techniques for Reducing Pesticide Use: Environmental and Economic Benefits*, pp. 51–78. Chichester, UK: John Wiley & Sons.

Pimentel, D. and K. Hart. 2001. Pesticide use: Ethical, environmental, and public health implications. In W. Galston and E. Shurr (eds.), *New Dimensions in Bioethics: Science, Ethics and the Formulation of Public Policy*, pp. 79–108. Boston, MA: Kluwer Academic Publishers.

Pimentel, D., L. McLaughlin, A. Zepp, et al. 1991. Environmental and economic impacts of reducing U.S. agricultural pesticide use. In D. Pimentel (ed.), *Handbook on Pest Management in Agriculture*, pp. 679–718. Boca Raton, FL: CRC Press.

Pimentel, D., U. Stachow, D.A. Takacs, et al. 1992. Conserving biological diversity in agricultural/forestry systems. *BioScience* 42: 354–362.

Pimentel, D., H. Acquay, M. Biltonen, et al. 1993a. Assessment of environmental and economic impacts of pesticide use. In D. Pimentel and H. Lehman (eds.), *The Pesticide Question: Environment, Economics and Ethics*, pp. 47–84. New York: Chapman & Hall.

Pimentel, D., L. McLaughlin, A. Zepp, et al. 1993b. Environmental and economic effects of reducing pesticide use in agriculture. *Agriculture, Ecosystems and Environment* 46(1–4): 273–288.

Pimentel, D., C. Wilson, C. McCullum, et al. 1997. Economic and environmental benefits of biodiversity. *BioScience* 47(11): 747–757.

Potter, D.A. and S.K. Braman. 1991. Ecology and management of turfgrass insects. *Annual Review of Entomology* 36: 383–406.

Potts, G.R. 1986. *The Partridge: Pesticides, Predation and Conservation*. London: Collins.

Reddy, V.R., D.N. Baker, F.D. Whisler, et al. 1987. Application of GOSSYM to yield decline in cotton. I. Systems analysis of effects of herbicides on growth, development and yield. *Agronomical Journal* 79: 42–47.

Repetto, R. and S.S. Baliga. 1996. *Pesticides and the Immune System: The Public Health Risks*. Washington, D.C.: World Resources Institute.

Richter, E.D. 2002. Acute human pesticide poisonings. In D. Pimentel (ed.), *Encyclopedia of Pest Management*, pp. 3–6. New York: Marcel Dekker.

Stone, W.B. and P.B. Gradoni. 1985. Wildlife mortality related to the use of the pesticide diazinon. *Northeastern Environmental Science* 4: 30–38.

Stringer, A. and C. Lyons. 1974. The effect of benomyl and thiophanate-methyl on earthworm populations in apple orchards. *Pesticide Science* 5: 189–196.

Stuart, S. 2003. Development of Resistance in Pest Populations. http://www.nd.edu/~chem191/e2.html (January 20, 2003).

Trumbel, J.T., W. Carson, H. Nakakihara, et al. 1988. Impact of pesticides for tomato fruit worm (Lepidoptera: Noctuidae) suppression on photosynthesis, yield, and non-target arthropods in strawberries. *Journal of Economic Entomology* 81: 608–614.

UFW. 2002. Latino Farmworkers Face Greater Risk of Cancer. http://www.faultline.org/new/2002/08/UFWcancer.html (January 18, 2003).

UNEP. 1979. *The State of the Environment: Selected Topics-1979*. Nairobi: United National Environment Program, Governing Council, Seventh Session.

Unnevehr, L.J., F.M. Lowe, D. Pimentel, et al. 2003. *Frontiers in Agricultural Research: Food, Health, Environment, and Communities*. Washington, D.C.: National Academies of Science.

USCB. 1990. *Statistical Abstract of the United States*. Washington, D.C.: U.S. Census Bureau.

USFWS. 1988. 1985 Survey of Fishing, Hunting and Wildlife Associated Recreation, Washington, D.C.: US Fish and Wildlife Service, US Department of the Interior.

USGS. 1995. Pesticides in Public Supply Wells of Washington State. http://wa.water.usgs.gov/ccpt/pubs/fs-122-96.html (January 21, 2003).

USGS. 1996. Pesticides Found in Ground Water below Orchards in the Quincy and Pasco Basin. http://wa.water.usgs.gov/ccpt/pubs/fs-171-96.html (January 21, 2003).

Weiner, B.P. and R.M. Worth (eds.). 1972. Insecticides: Household use and respiratory impairment. In *Adverse Effects of Common Environmental Pollutants*, pp. 149–151. New York: MSS Information Corporation.

Well Owner. 2003. The Use of Ground Water. http://www.wellowner.org/useof.html (January 21, 2003).

White, D.H., C.A. Mitchell, L.D. Wynn, et al. 1982. Organophosphate insecticide poisoning of Canada geese in the Texas Panhandle. *Journal of Field Ornithology* 53: 22–27.

White, L. 1967. The historical roots of our ecological crisis. *Science* 155: 1203–1207.

WHO. 1997. Malaria: A statistical index. World Health Organization, Geneva. *The Scientist* 11(10): 6 (May 12, 1997).

14 Water Resources: Agricultural and Environmental Issues

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Water is essential for maintaining an adequate food supply and a productive environment for the human population, plants, animals, and microbes on the Earth. Per capita food supplies (cereal grains) have been decreasing for nearly 20 years (declined 17%), in part because of shortages of freshwater, cropland, and the concurrent increase in human numbers (FAO, 1961–2002). Shortages in food supplies have in part contributed to more than 3 billion malnourished people in the world (WHO, 2004a). Two of the most serious malnutrition problems include iron deficiency affecting 2 billion people and protein/calorie deficiencies affecting nearly 800 million people (WHO, 2002, 2004b). The iron deficiency and protein/calorie deficiency each result in about 0.8 million deaths each year (WHO, 2002). Humans obtain all their nutrients from crops and livestock and these nutrient sources require water, land, and energy for production (Pimentel et al., 2004).

Consider that the world population currently numbers 6.3 billion with over a quarter million people added each day (PRB, 2003). The UN (2001) estimates that approximately 9.4 billion people will be present by 2050. In addition, freshwater demand worldwide has been increasing rapidly as population and economies grow (Hinrichsen et al., 1998; Postel, 1999; Rosengrant et al., 2002; Shiklomanov and Rodda, 2003; UNEP, 2003a; Gleick, 2004). Population growth, accompanied by increased water use, will not only severely reduce water availability per person, but will stress all biodiversity in the entire global ecosystem (Pimentel et al., 2004).

Major factors influence water availability including rainfall, temperature, evaporation rates, soil quality, vegetation type, as well as water runoff. Furthermore, serious difficulties already exist in allocating the world's freshwater resources fairly between and within countries. These conflicts are escalating among new industrial, agricultural, and urban sectors. Overall, water shortages severely reduce biodiversity in both aquatic and terrestrial ecosystems, while water pollution facilitates the spread of serious human diseases and diminishes water quality (Postel et al., 1996, 2004).

In this chapter, water utilization by individuals and especially agricultural systems is analyzed. Interrelationships that exist among population growth, water use and distribution, the status of biodiversity, the natural environment, plus the impacts of water borne human diseases are reported.

WATER RESOURCES

HYDROLOGIC CYCLE

Of the estimated 1.4×10^{18} m^3 of water on the Earth, more than 97% is in the oceans (Shiklomanov and Rodda, 2003). Approximately 35×10^{15} m^3 of the Earth's water is freshwater, of which about 0.3% is held in rivers, lakes, and reservoirs (Shiklomanov and Rodda, 2003). The remainder of freshwater is stored in glaciers, permanent snow, and groundwater aquifers. The Earth's atmosphere contains about 13×10^{12} m^3 of water, and is the source of all the rain that falls on Earth (Shiklomanov and Rodda, 2003). Yearly, about 151,000 quads (quad = 10^{15} BTU) of solar energy cause evaporation and move about 577×10^{12} m^3 of water from the Earth's surface into the atmosphere. Of this evaporation, 86% is from the oceans (Shiklomanov, 1993). Although only 14% of the water evaporation is from land, about 20% (115×10^{12} m^3 per year) of the world's precipitation falls on land with the surplus water returning to the oceans via rivers (Shiklomanov, 1993). Thus, each year, solar energy transfers a significant portion of water from the oceans to land areas. This aspect of the hydrologic cycle is vital not only to agriculture but also to human life and natural ecosystems (Pimentel et al., 2004).

AVAILABILITY OF WATER

Although water is considered a renewable resource because it is replenished by rainfall, its availability is finite in terms of the amount available per unit time in any one region. The average precipitation for most continents is about 700 mm/year (7 million L/ha/year), but varies among and within them (Shiklomanov and Rodda, 2003). In general, a nation is considered water scarce when the availability of water drops below 1,000,000 L/capita/year (Engelman and Le Roy, 1993) (Table 14.1). Thus Africa, despite having an average of 640 mm/year of rainfall, is relatively arid as its high temperatures and winds foster rapid evaporation (Pimentel et al., 2004).

Regions that receive low rainfall (less than 500 mm/year) experience serious water shortages and inadequate crop yields. For example, 9 of the 14 Middle Eastern countries (including Egypt, Jordan, Israel, Syria, Iraq, Iran, and Saudi Arabia) have insufficient freshwater (Myers and Kent, 2001; UNEP, 2003a) (Table 14.1).

Substantial withdrawals from lakes, rivers, groundwater, and reservoirs that are used to meet the needs of individuals, cities, farms, and industries already stresses the availability of water in some parts of the United States (Alley et al., 1999). When managing water resources, the total agricultural, societal, and environmental system must be considered. Legislation is sometimes required to ensure a fair allocation of water. For example, laws determine the amount of water that must be left in the Pecos River in New Mexico to ensure sufficient water flows into Texas (Pimentel et al., 2004).

TABLE 14.1

Regions of the World with Water Problems (Based on the Criterion That Yearly Water Availability per Capita Is Less Than 1,000,000 L/year) and Their per Capita Water Availability (Falkenmark and Lindh, 1993)

Region	Water Availability per Capita 1000 L/year
Egypt	40
West Bank	126
Jordan	255
Saudi Arabia	300
Israel	376
Syria	440
Kenya	610
United States (comparison)	1862

Source: *BioScience* 54(10), 909–918. With permission. Copyright American Institute of Biological Sciences.

GROUNDWATER RESOURCES

Approximately 30% (11×10^{15} m^3) of all freshwater on Earth is stored as groundwater. The amount of water held as groundwater is more than 100 times the amount collected in rivers and lakes (Shiklomanov and Rodda, 2003). Most groundwater has accumulated over millions of years in vast aquifers located below the surface of the Earth. Aquifers are replenished slowly by rainfall, with an average recharge rate that ranges from 0.1% to 3% per year (Pimentel et al., 2004). Assuming an average of 1% recharge rate, only 110×10^{12} m^3 of water per year is available for sustainable use worldwide. At present, world groundwater aquifers provide approximately 23% of all water used throughout the world (USGS, 2003a). Irrigation for U.S. agriculture relies heavily upon groundwater, with 65% of irrigation water being pumped from aquifers (Pimentel et al., 2004).

Population growth, increased irrigated agriculture, and other water uses are mining groundwater resources. Specifically, the uncontrolled rate of water withdrawal from aquifers is significantly faster than the natural rate of recharge, causing water tables to fall by more than 30 m in some U.S. regions from 1950 to 1990 (Brown, 2002). The overdraft of global groundwater is estimated to be about 200×10^9 m^3 or nearly twice the average recharge rate (Pimentel et al., 2004).

For example, the capacity of the U.S. Ogallala aquifer, which underlies parts of Nebraska, South Dakota, Colorado, Kansas, Oklahoma, New Mexico, and Texas, has decreased 33% since about 1950. Withdrawal from the Ogalla is three times faster than its recharge rate (Gleick et al., 2002). Aquifers are being withdrawn more than 10 times faster than the recharge rate of aquifers in parts of Arizona (Gleick et al., 2002).

Similar problems exist throughout the world. For example, in the agriculturally productive Chenaran Plain in northeastern Iran, the water table has been declining by 2.8 m/year since the late 1990s (Brown, 2002). Withdrawal in Guanajuato, Mexico, has caused the water table to fall by as much as 3.3 m per year (Brown, 2002). The rapid depletion of groundwater poses a serious threat to water supplies in world agricultural regions especially for irrigation. Furthermore, when some aquifers are mined, the surface soil area is prone to sink, resulting in the inability of an aquifer to be refilled (Pimentel et al., 2004).

STORED WATER RESOURCES

In the United States, many dams were built during the early twentieth century in arid regions in an effort to increase the available quantities of water. Although the era of constructing large dams and associated conveyance systems to meet water demand has slowed down in the United States (Pimentel et al., 2004), dam construction continues in many developing countries worldwide.

Given that the expected life of a dam is 50 years, 85% of U.S. dams will be more than 50 years old by 2020 (Pimentel et al., 2004). Prospects for the construction of new dams in the United States do not appear encouraging. Over time, the capacity of all dams is reduced as silt accumulates behind them. Estimates are that 1% of the storage capacity of the world's dams is lost due to silt each year (Pimentel et al., 2004).

WATER USE

Water from different resources is withdrawn both for *use* and *consumption* in diverse human activities. The term *use* refers to all human activities for which some of the withdrawn water is returned for reuse, for example, cooking water, wash water, and waste water. In contrast, *consumption* means that the withdrawn water is nonrecoverable. For example, evapotranspiration of water from plants is released into the atmosphere and is considered nonrecoverable.

HUMAN WATER USE

The water content of living organisms ranges from 60% to 95%; humans are about 60% water (Pimentel et al., 2004). To sustain health, humans should drink from 1.5 to 2.5 L of water/person/day. In addition to drinking water, Americans use about 400 L water/person/day for cooking, washing, disposing of wastes, and other personal uses (USBC, 2003). In contrast, 83 other countries report an average below 100 liters/person/day of water for personal use (Gleick et al., 2002).

Currently the U.S. freshwater withdrawals, including that for irrigation, total about 1600 billion L/day or about 5700 L of water/person/day. Of this amount about 80% comes from surface water and 20% is withdrawn from groundwater resources (USBC, 2003). Worldwide, the average withdrawal is 1970 L/person/day for all purposes (Gleick et al., 2002). Approximately 70% of the water withdrawn is consumed and is nonrecoverable worldwide.

AGRICULTURE AND WATER

WATER IN CROP PRODUCTION

Plants require water for photosynthesis, growth, and reproduction. Water used by plants is nonrecoverable, because some water becomes a part of the plant chemically and the remainder is released into the atmosphere. The processes of carbon dioxide fixation and temperature control require plants to transpire enormous amounts of water. Various crops transpire water at rates between 600 and 2000 L of water per kilogram of dry matter of crops produced (Table 14.2). The average global transfer of water into the atmosphere from the terrestrial ecosystems by vegetation transpiration is estimated to be about 64% of all precipitation that falls to Earth (Pimentel et al., 2004).

The minimum soil moisture essential for crop growth varies. For instance, U.S. potatoes require 25%–50%, alfalfa 30%–50%, and corn 50%–70% (Pimentel et al., 2004), while rice in China is reported to require at least 80% soil moisture (Pimentel et al., 2004). Rainfall patterns, temperature, vegetative cover, high levels of soil organic matter, active soil biota, and water runoff all affect the percolation of rainfall into the soil where it will be used by plants.

The water required by food and forage crops ranges from 600 to 3000 L of water per kilogram (dry) of crop yield (Table 14.2). For instance, a hectare of U.S. corn, with a yield of approximately 9000 kg/ha, transpires about 6 million L/ha of water during the growing season (Pimentel et al., 2004), while an additional

TABLE 14.2
Estimated Amount of Water Required to Produce Crops and Livestock (Pimentel et al., 2004)

Crop and Livestock	L/kg
Soybeans	2,000
Rice	1,600
Sorghum	1,300
Alfalfa	1,100
Wheat	900
Corn	650
Potatoes (dry)	630
Millet	272
Broiler chicken	3,500
Pig	6,000
Beef	43,000
Sheep	51,000

Source: *BioScience* 54(10), 909–918. With permission. Copyright American Institute of Biological Sciences.

1–2.5 million L/ha of soil moisture evaporate into the atmosphere (Pimentel et al., 2004). This means that about 800 mm (8 million L/ha) of rainfall are required during the growing season for corn production. Even with 800–1000 mm of annual rainfall in the U.S. Corn-Belt region, corn frequently suffers from insufficient water during the critical summer growing period (Pimentel et al., 2004).

A hectare of high yielding rice requires approximately 11 million L/ha of water for an average yield of 7 t/ha (metric tons per hectare) (Pimentel et al., 2004). On average, soybeans require about 5.8 million L/ha of water for a yield of 3 t/ha (Pimentel et al., 2004). In contrast, wheat that produces less plant biomass than either corn or rice requires only about 2.4 million L/ha of water for a yield of 2.7 t/ha (Table 14.2). Note, under semi-arid conditions, yields of nonirrigated crops, such as corn, are low (1–2.5 t/ha) even when ample amounts of fertilizers are applied (Pimentel et al., 2004).

IRRIGATED CROPS AND LAND USE

World agriculture consumes approximately 70% of freshwater withdrawn per year (UNESCO, 2001a). Approximately 17% of the world's cropland is irrigated but produces 40% of the world's food (FAO, 2002). Worldwide, the amount of irrigated land is slowly expanding, even though salinization, water logging, and siltation continue to decrease its productivity (Gleick, 2002). Despite a small annual increase in total irrigated areas, the per capita irrigated area has been declining since 1990, due to rapid population growth (Postel, 1999; Gleick, 2002). Specifically, global irrigation per capita has declined nearly 10% during the past decade (Postel, 1999; Gleick, 2002), while in the United States irrigated land per capita has remained constant at about 0.08 ha (USDA, 2003).

Irrigated U.S. agricultural production accounts for about 40% of freshwater withdrawn (USGS, 2003b), and more than 80% of the water consumed (Pimentel et al., 2004). California agriculture accounts for 3% of the state's economic production, but consumes 85% of the water withdrawn (Myers and Kent, 2001).

ENERGY USE IN IRRIGATION

Irrigation requires a significant expenditure of fossil energy both for pumping and delivering water to crops. Annually in the United States, we estimate 15% of the total energy expended for all crop production is used to pump irrigation water (Pimentel et al., 2004). Overall the amount of energy consumed in irrigated crop production is substantially greater than that expended for rainfed crops. For example, irrigated wheat requires the expenditure of three times more energy than rainfed wheat. Specifically, about 4.2 million kcal/ha/year is the required energy input for rainfed wheat, while irrigated wheat requires 14.3 million kcal/ha/year to apply an average of 5.5 million L of water (Pimentel et al., 2004).

Delivering the 10 million L of irrigation water needed by a hectare of irrigated corn from surface water sources requires the expenditure of about 880 kWh/ha of fossil fuel (Batty and Keller, 1980). In contrast, when irrigation water must be pumped from a depth of 100 m, the energy cost increases up to 28,500 kWh/ha, or more than 32 times the cost of surface water (Gleick, 1993).

The costs of irrigation for energy and capital are significant. The average cost to develop irrigated land ranges from $3800/ha to $7700/ha (Postel, 1999). Thus, farmers must not only evaluate the dollar cost of developing irrigated land, but must also consider the annual costs of irrigation pumping. For example, delivering 7–10 million L/ha of water costs around $750–$1000 (Pimentel et al., 2004). About 150,000 ha of agricultural land have already been abandoned in the United States due to high pumping costs (Pimentel et al., 2004).

The large quantities of energy required to pump irrigation water are significant considerations both from the standpoint of energy and water resource management. For example, approximately 8 million kcal of fossil energy are expended for machinery, fuel, fertilizers, pesticides, and partial (15%) irrigation, to produce 1 ha of rainfed U.S. corn (Pimentel et al., 2004). In contrast, if the corn crop were fully irrigated, the total energy inputs would rise to nearly 25 million kcal/ha (2500 L of oil equivalents) (Pimentel et al., 2004). In the future, this energy dependency will not only influence the overall economics of irrigated crops but also the selection of specific crops worth irrigating (Pimentel et al., 2004) (Table 14.2). While a low value crop, like alfalfa, may be uneconomical, other crops might use less water plus have a higher market value (Table 14.2).

The efficiency varies with irrigation technologies (Pimentel et al., 2004). The most common irrigation methods, flood irrigation and sprinkler irrigation, frequently waste water. In contrast, the use of more focused application methods, such as "drip" or "microirrigation," have found favor because of their increased water efficiency. Drip irrigation delivers water to individual plants by plastic tubes and uses from 30% to 50% less water than surface irrigation. In addition to conserving water, drip irrigation reduces the problems of salinization and waterlogging (Tuijl, 1993). Although drip systems achieve up to 95% water efficiency, they are expensive, may be energy intensive, and require clean water to prevent the clogging of the fine delivery tubes (Pimentel et al., 2004).

Soil Salinization and Waterlogging in Irrigation

With rainfed crops, salinization is not a problem because the salts are naturally flushed away. But when irrigation water is applied to crops and returns to the atmosphere via plant transpiration and evaporation, dissolved salts concentrate in the soil where they inhibit plant growth. The practice of applying about 10 million L of irrigation water per hectare each year results in approximately 5 t/ha of salts being added to the soil (Bouwer, 2002). The salt deposits can be flushed away with added fresh water but at a significant cost (Bouwer, 2002). Worldwide, approximately half of all existing irrigated soils are adversely affected by salinization (Hinrichsen et al., 1998). Each year the amount of world agricultural land destroyed by salinized soil is estimated to be 10 million ha (Pimentel et al., 2004).

In addition, drainage water from irrigated cropland contains large quantities of salt. For instance, as the Colorado River flows through Grand Valley, Colorado, it picks up 580,000 tons of salts per year (USDI, 2001). Based on the drainage area of 20,000 ha, the water returned to the Colorado River contains an estimated 30 t/ha of salts per year (Pugh, 2001). In Arizona, the Salt River and Colorado River deliver a total of 1.6 million tons of salt into south-central Arizona each year (Pimentel et al., 2004).

Waterlogging is another problem associated with irrigation. Over time, seepage from irrigation canals and irrigated fields cause water to accumulate in the upper soil levels. Due to water losses during pumping and transport, approximately 60% of the water intended for crop irrigation never reaches the crop (Wallace, 2000). In the absence of adequate drainage, water tables rise in the upper soil levels, including the plant root zone, and crop growth is impaired. Such irrigated fields are sometimes referred to as "wet deserts" because they are rendered unproductive (Pimentel et al., 2004). For example, in India, waterlogging adversely affects 8.5 million ha of cropland and results in the loss of as much as 2 million tons of grain every year (Pimentel et al., 2004). To prevent both salinization and waterlogging, sufficient water along with adequate soil drainage must be available to ensure salts and excess water are drained from the soil.

WATER RUNOFF AND SOIL EROSION

As more than 99% of world food supply comes from the land, the adequacy of this supply depends on the continued availability of productive soils (FAO, 1998). Erosion adversely affects crop productivity by reducing the availability of water, diminishing soil nutrients, soil biota, and soil organic matter, and also decreasing soil depth (Pimentel et al., 2004). The reduction in the amount of water available to the growing plants is considered the most harmful effect of erosion, because eroded soil absorbs 87% less water by infiltration than uneroded soils (Guenette, 2001). Soybean and oat plantings intercept approximately 10% of the rainfall, whereas tree canopies intercept 15%–35% (Pimentel et al., 2004). Thus, the removal of trees increases water runoff and reduces water availability.

A water runoff rate of about 30% of total rainfall of 800 mm/year causes significant water shortages for growing crops, like corn, and ultimately lowering crop yields (Pimentel et al., 2004). In addition, water runoff, which carries sediments, nutrients, and pesticides from agricultural fields, into surface and ground waters, is the leading cause of nonpoint source pollution in the United States (EPA, 2002). Thus, soil erosion is a self-degrading cycle on agricultural land. As erosion removes topsoil and organic matter, water runoff is intensified and crop yields decrease. The cycle is repeated again with even greater intensity during subsequent rains.

Increasing soil organic matter by applying manure or similar materials can improve the water infiltration rate by as much as 150% (Guenette, 2001). In addition, using vegetative cover, such as intercropping and grass strips, helps slow both water runoff and erosion (Lal, 1993). For example, when silage corn is interplanted with red clover, water runoff can be reduced by as much as 87% and soil loss can be reduced by 78% (Pimentel et al., 2004). Reducing water runoff in these and other ways is an important step in increasing water availability to crops, conserving water resources, decreasing nonpoint source pollution, and ultimately decreasing water shortages (NGS, 1995).

Planting trees to serve as shelter belts between fields reduces evapotranspiration from the crop ecosystem by up to 20% during the growing season, thereby reducing nonpoint source pollution (Pimentel et al., 2004), and increases some crop yields, such as potatoes and peanuts (Snell, 1997). If soil and water conservation measures are not implemented, the loss of water for crops via soil erosion can amount to as much as 5 million L/ha/year (Pimentel et al., 2004).

WATER USE IN LIVESTOCK PRODUCTION

The production of animal protein requires significantly more water than the production of plant protein (Pimentel et al., 2004). Although U.S. livestock directly use only 2% of the total water used in agriculture (Solley et al., 1998), the water inputs for livestock production are substantial because water is required for the forage and grain crops.

Each year, a total of 253 million tons of grain are fed to U.S. livestock requiring a total of about 250×10^{12} L of water (Pimentel et al., 2004). Worldwide grain production specifically for livestock requires nearly three times the amount of grain that is fed to U.S. livestock and three times the amount of water used in the United States to produce the grain feed (Pimentel et al., 2004).

Animal products vary in the amounts of water required for their production (Table 14.2). For example, to produce 1 kg of chicken one requires 3500 L of water while to produce 1 kg of sheep one requires approximately 51,000 L of water to produce the required 21 kg of grain and 30 kg of forage to feed these animals (USDA, 2003; Pimentel et al., 2004) (Table 14.2). For open rangeland (instead of confined feedlot production), from 120 kg to 200 kg of forage are required to produce 1 kg of beef. This amount of forage requires 120,000–200,000 L of water per kilogram of beef (Pimentel et al., 2004). Beef cattle can be produced on rangeland, but a minimum of 200 mm per year of rainfall is needed (Pimentel et al., 2004).

U.S. agricultural production is projected to expand to meet the increased food needs of a U.S. population that is projected to double in the next 70 years (USBC, 2003). The food situation is expected to be more serious in developing countries, such as Egypt and Kenya, because of rapidly growing populations (Rosengrant et al., 2002). Increasing crop yields necessitates a parallel increase in freshwater utilization in agriculture. Therefore, increased crop and livestock production during the next five to seven decades will significantly increase the demand on all water resources, especially in the western, southern, and central United States (USDA, 2003), as well as in many regions of the world with low rainfall.

WATER POLLUTION AND HUMAN DISEASES

Closely associated with the overall availability of water resources is the problem of water pollution and human diseases. At present, approximately 20% of the world's population lacks safe drinking water, and nearly half the world population lacks adequate sanitation (GEF, 2002; UN, 2002). This problem is acute in many developing countries that discharge an estimated 95% of their untreated urban sewage directly into surface waters (Pimentel et al., 2004). For example, of India's 3119 towns and cities, only 8 have full wastewater treatment facilities (WHO, 1992). Downstream, the untreated water is used for drinking, bathing, and washing, resulting in serious human infections and illnesses.

Overall, waterborne infections account for 90% of all human infectious diseases in developing countries (Pimentel et al., 2004). Lack of sanitary conditions contributes to approximately 12 million deaths each year, primarily among infants and young children (Hinrichsen et al., 1998).

Approximately 40% of U.S. freshwater is deemed unfit for recreational or drinking water uses because of contamination with dangerous microorganisms, pesticides, and fertilizers (UNESCO, 2001b). In the United States, waterborne infections account for approximately 940,000 infections and approximately 900 deaths each year (Pimentel et al., 2004). In recent decades, more U.S. livestock production systems have moved closer to urban areas, causing water and foods to be contaminated with manure (NAS, 2003). In the United States, the quantity of livestock manure and other wastes produced each year are estimated to be 1.5 billion tons (Pimentel et al., 2004). Associated with this kind of contamination, the Centers for Disease Control reports that more than 76 million Americans are infected each year with pathogenic *E. coli* and related foodborne pathogens, resulting in about 5000 deaths per year (DeWaal et al., 2000).

The incidence of schistosomiasis, which is also associated with contaminated freshwater, is expanding worldwide and each year infects more than 200 million people and currently causes an estimated 20,000 deaths per year (Hinrichsen et al., 1998). Its spread is associated with an increase in habitats, including the construction of dams and irrigation canals suitable for the snail intermediate-host population and accessible for humans to come in contact with the infected water (Shiklomanov, 1993). For example, construction of the Aswan High Dam in Egypt and related irrigation systems in 1968 led to an explosion of *Schistosoma mansoni* in the human population; increasing from 5% in 1968 to 77% of all Egyptians in 1993 (Shiklomanov, 1993). In 1986, the construction of a dam in Senegal resulted in an increase in schistosomiasis from 0% in 1986 to 90% by 1994 (Pimentel et al., 2004).

Mosquito-borne malaria is also associated with water bodies. Worldwide this disease presently infects more than 2.4 billion people (Pimentel et al., 2004) and kills about 2.7 million each year (Pimentel et al., 2004). Environmental changes, including polluted water, have fostered this high incidence and increase in malaria. For instance, deforestation in parts of Africa exposes land to sunlight and promotes the development of temporary pools of water that favor the breeding of human-biting, malaria-transmitting mosquitoes, *Anopheles gambiae* (Pimentel et al., 2004). In addition, with many African populations doubling every 20 years (PRB, 2003), more people are living in close proximity to mosquito-infested aquatic ecosystems. Concurrently, the mosquito vectors are evolving resistance to insecticides that pollute their aquatic ecosystems, while protozoan pathogens are evolving resistance to the over-used antimalarial drugs. Together these factors are reducing the effectiveness of many malaria control efforts (Pimentel et al., 2004).

Another serious waterborne infectious disease that can be transmitted via air, water, and food is tuberculosis (TB). At present, approximately 2 billion people are infected with TB with the number increasing each year (Pimentel et al., 2004).

Presently, about 2 billion people worldwide are infected with one or more helminth species, either by direct penetration or by use of contaminated water or food (Hotez et al., 1996). In locations where sanitation is poor and overcrowding is rampant, as in parts of urban Africa, up to 90% of the population may be infected with one or more helminthes (Pimentel et al., 2004).

In addition to helminthes and microbe pathogens, there are many chemicals that contaminate water and have negative impacts on human health as well as natural biota.

For example, an estimated 3 billion kg of pesticides are applied worldwide each year in agriculture (Pimentel et al., 2004). USEPA also allowed the application of sludge to agricultural land and this sludge is contaminated with heavy metals and other toxics (Pimentel et al., 2004). Many of these agricultural chemicals, including nitrogen fertilizer, contaminate aquatic ecosystems by leaching and runoff and result in eutrophication of aquatic ecosystems and other environmental problems (Howarth, 2003). Pesticides alone contribute to an estimated 26 million human poisonings and 220,000 deaths each year worldwide (Richter, 2002).

LIMITS TO WATER USE

Costs of Water Treatment

Increases in pollution of surface and groundwater resources not only pose a threat to public and environmental health, but also contribute to the high costs of water treatment, thus further limiting the availability of water for use. Depending on water quality and the purification treatments used, potable water costs an average of 50¢/1000 L in the United States and range up to $1.91/1000 L in Germany (UNESCO, 2001c). Appropriate water pricing is important for improved water demand and conservation of water (UNESCO, 2001d; Pimentel et al., 2004).

The cost of treating U.S. sewage for release into streams and lakes ranges from 55¢/1000 L for small plants to 30¢/1000 L for large plants (Gleick, 2000). Sewage effluent, when properly treated to make it safe for use as potable water, is relatively expensive and ranges in costs from $1.00 to $2.65/1000 L (Gleick, 2000).

Purifying and reducing the number of polluting microbes in water, as measured by the BOD (biological oxygen demand), is energy costly. Removing 1 kg of BOD requires 1 kWh (Pimentel et al., 2004). In this process, most of the cost for pumping and delivering water is for energy and equipment. Delivering 1 m^3 (1000 L) of water in the United States requires the expenditure of about 1.3 kWh. Excluding only the energy for pumping sewage, the cost and amount of energy required to process 1000 L of sewage in a technologically advanced wastewater treatment plant is about 65¢ and requires about 0.44 kWh of energy (Pimentel et al., 2004). Looking to the future, the costs of water treatment and the energy required to purify water will increase.

Dependence on the oceans for freshwater has major problems. When brackish water is desalinized, the energy costs are high, ranging from 25¢ to 60¢/1000 L, while seawater desalinization ranges from 75¢ to $3/1000 L (Buros, 2000). In addition, transporting large volumes of desalinized water adds to the costs.

Economic Costs of Water Subsidies

The relatively high cost of treating and delivering water has led many world governments to subsidize water for agriculture and household use. For example, some U.S. farmers pay as little as 1–5¢/1000 L they use in irrigation, while the public pays from 30¢ to 80¢ per 1000 L of treated water for personal use (Gleick, 2000). Farmers in the Imperial Irrigation District of California pay $15.50 in delivery fees for 1.2 million L of water (Murphy, 2003). Some investigators suggest that if U.S.

farmers paid the full cost of water, they would have to conserve and manage irrigation water more effectively (Pimentel et al., 2004).

The construction cost subsidy for federally subsidized western U.S. irrigated cropland amounts to about \$5000 per hectare (Pimentel et al., 2004), and represents an annual construction cost subsidy of about \$440 per ha/year over the life of the project (Pimentel et al., 2004). The total annual government subsidy is estimated to range from \$2.5 billion to \$4.4 billion for the 4.5 million ha of irrigated land in the western United States (Myers and Kent, 2001; VanBeers and deMoor, 2001). Worldwide, from 1994 to 1998 governmental water subsidies totaled \$45 billion per year for non-OECD (Organization for Economic Cooperation and Development) countries and \$15 billion for OECD countries (VanBeers and deMoor, 2001). During the same period, agricultural subsidies per year total \$65 billion for non-OECD and \$355 billion for OECD countries (VanBeers and deMoor, 2001).

According to the World Bank (2003), the objectives of fair water pricing are (1) to seek revenue to pay for the operations and maintenance of water availability, (2) improve water-use efficiency, and (3) recover the full costs of water pumping and treatment. However, in general there appear to be problems with some private, for-profit companies operating water systems for communities and regions. Often the companies operate as monopolies that can lead to pricing problems (Schalch, 2003).

If U.S. prices of gasoline and diesel energy increase significantly, it follows that irrigation costs will also escalate from the current approximately \$3 billion per year (Pimentel et al., 2004). As vegetable and fruit crops return more per dollar invested in irrigation water than field crops, farmers may have to reassess the crops they grow. For example, in Israel 1000 L of water from irrigation produces 79¢ worth of groundnuts and 57¢ worth of tomatoes, but only 13¢ worth of corn grain and 12¢ worth of wheat (Pimentel et al., 2004).

LOSS OF BIODIVERSITY

Natural diversity of species is essential to maintaining a productive environment, as well as productive agriculture and forestry. The water required to keep natural ecosystems, especially the plants, functioning has been appropriately termed *green water* (Falkenmark, 1995).

The biodiversity of all species throughout the world is adversely affected when water resources are reduced or polluted. Thus the drastic drainage of more than half of U.S. wetlands (Pimentel et al., 2004) that contain 45% of our federally endangered and threatened species has seriously disrupted these ecosystems (Havera et al., 1997). In 2002, approximately 33,000 salmon perished in the Klamath River when farmers were allowed to withdraw increased volumes of water for irrigation (Pimentel et al., 2004). Pear farmers in the Rogue Valley of Oregon use significant amounts of the water before it reaches the Klamath Lake, leaving only 616 million m^3 of water per year for wildlife and other farmers downstream (Fattig, 2001). Similarly, overpumping and upstream removal of water have reduced biodiversity in the Colorado River and the Rio Grande River (Pimentel et al., 2004). The major alteration in the natural water flow in the lower portion of the U.S. Colorado River has been responsible for 45 species of plants and animals to be listed as federally endangered or threatened (Glenn et al., 2001).

EFFECT OF CLIMATE AND ENVIRONMENTAL CHANGE ON WATER AVAILABILITY

Estimates of water resources and their future availability can only be based on present world climate patterns. The continued loss of forests and other vegetation, and the accumulation of carbon dioxide, methane gas, and nitrous oxides in the atmosphere, are projected to lead to global climate change. Over time, such changes may alter present precipitation and temperature patterns throughout the world (Downing and Parry, 1994; IPCC, 2002). With major shifts in water availability, future agricultural, forestry, biodiversity, and diverse human activities will be impacted.

For example, if, as projected, California experiences a 50% decrease in mountain snowpack due to global warming (Knowles and Cayan, 2003), this would change both the timing and intensity of seasonal surface water flow (Pimentel et al., 2004). In contrast, Canada might benefit from warming with extended growing seasons, but even this region eventually could face water shortages (Parry and Carter, 1989; IPCC, 2002). If, as projected, the annual temperatures in the U.S. Corn-Belt rise 3°C–4°C, rainfall might decline by about 10% (Myers and Kent, 2001), and evaporation rates from the soil may increase and limit corn production in the future (Pimentel et al., 2004).

The predicted global warming, along with increased human food requirements, can be expected to alter and probably increase world irrigation needs by 30% to ensure food security (Doll, 2002). Other serious impacts of global warming could increase deforestation, desertification, soil erosion, and loss of biodiversity. All of these major changes suggest the reduction in the availability of water for humans, for all other living organisms, and also for crop and forest production (Root et al., 2003).

CONFLICTS OVER WATER USE

The rapid rise in withdrawal of freshwater for agricultural irrigation and for other uses that have accompanied population growth has spurred serious conflicts over water resources both within and between countries (FAO, 2000). In part, the conflicts over fresh water are due to the sharing of freshwater by countries and regions. Currently, there are 263 transboundary river basins sharing water resources (UNESCO, 2001d). Worldwide such conflicts have increased from an average of 5 per year in the 1980s to 22 in 2000 (GEF, 2002). In 23 countries where data are available, conflicts related to agricultural use of water cost an estimated $55 billion between 1990 and 1997 (GEF, 2002).

At least 20 nations obtain more than half their water from rivers that cross national boundaries (Gleick, 1993), and 14 countries receive 70% or more of their surface water resources from rivers that are outside their borders (Alavian, 2003; Cech, 2003). For example, Egypt obtains 97% of its freshwater from the Nile River (Alavian, 2003), the second longest in the world, which is also shared by 10 other countries (Alavian, 2003). Indeed, the Nile River is so overused that during parts of the year little or no freshwater reaches the Mediterranean Sea (Pimentel et al., 2004).

Historically, the Middle East region has had the most conflicts over water, largely because it has less available water per capita than most other regions, and every major river crosses international borders (Gleick et al., 2002). Furthermore, the human populations in these countries are increasing rapidly, some having doubled in the last 20–25 years, placing additional stress on the difficult political climate (PRB, 2003).

The distribution of river water also creates conflicts between several U.S. states as well as problems between the United States and Mexico. California, Nevada, Colorado, New Mexico, Utah, Arizona, and Mexico all depend on Colorado River water. In a normal year, little water reaches Mexico, and little or no water reaches the Gulf of California (Postel et al., 1996; Gleick, 2000).

CONSERVING WATER RESOURCES

Conserving world water must be a priority of individuals, communities, and countries. An important approach is to find ways to facilitate the percolation of rainfall into the soil instead of allowing it to run off into streams and rivers. For example, the increased use of trees and shrubs make it possible to catch and slow water runoff by 10%–20%, thereby conserving water before it reaches streams, rivers, and lakes (Pimentel et al., 2004). This approach also reduces flooding.

Maintaining crop, livestock, and forest production requires conserving all water resources available, including rainfall. Some practical strategies that support water conservation for crop production include (1) monitoring soil water content; (2) adjusting water application needs to specific crops; (3) applying organic mulches to prevent water loss and improve water percolation, through reduced water runoff and evaporation; (4) using crop rotations that reduce water runoff; (5) preventing the removal of biomass from land; (6) increasing use of trees and shrubs to slow water runoff; and (7) employing precision irrigation in water delivery systems, such as drip irrigation, that will result in efficient crop watering (IRZ, 2002).

In forest areas, it will be necessary to avoid clear cutting and humans should employ sound forest management. Trees also benefit urban areas that have high rates of runoff. As water runoff is rapid from roofs, driveways, roads, and parking lots, the water can be collected in cisterns and constructed ponds. Estimated runoff rates from urban area were 72% higher than areas with forest cover (Boulder, 2002).

Given that many aquifers are being overdrafted, government efforts are needed to limit the pumping to sustainable withdrawal levels or at the known recharge rate. Integrated water resource management programs offer many opportunities to conserve water resources for everyone, farmers and the public.

USING WATER WISELY IN THE FUTURE

Providing adequate quantities of pure freshwater for humans and their diverse activities appears to be a major problem worldwide. If further competition for water resources within regions and between countries continues to escalate, and remain unresolved, this too will have negative impacts on essential freshwater supplies for personal and agricultural use. Even now, freshwater resources for food production and other human needs are declining because of increasing demand (UNEP, 2003b; Gleick, 2004) and becoming outright scarce in arid regions. Particularly in arid regions, where groundwater resources are the primary sources of water, future irrigation, industrial, and urban water use must be carefully managed to prevent exhausting the aquifers.

Priorities for using water wisely are as follows:

- Because agriculture consumes 70% of world's freshwater, farmers should be the prime target for incentives to conserve water.
- Implement water conserving irrigation practices, such as drip irrigation, to reduce water waste.
- Implement water/soil conservation practices, such as cover crops and crop rotations, to minimize rapid water runoff related to soil erosion.
- Reduce and eliminate water subsidies that encourage the wasteful use of water by farmers and others.
- Implement World Bank (2003) policies for the fair pricing of freshwater.
- Protect forests, wetlands, and natural ecosystems to enhance the conservation of water.
- Control water pollution to protect public health, agriculture, and the environment.

REFERENCES

Alavian, V. 2003. Shared waters: Catalyst for cooperation. http://www.uwin.siu.edu/ucowr/updates/pdf/V115_A2.pdf (1/20/2003).

Alley, W.M., T.E. Reilly, and O.L. Franke. 1999. Sustainability of ground-water resources. Denver, CO: United States Geologic Survey. Report 1186.

Batty, J.C. and J. Keller. 1980. Energy requirements for irrigation. In D. Pimentel (ed.), *Handbook of Energy Utilization in Agriculture*, pp. 35–44. Boca Raton, FL: CRC Press.

Boulder. 2002. Boulder's urban forest benefits stormwater runoff. http://www.ci.boulder.co.us/publicworks/depts/utilities/conservation/chapter_one.pdf (2/8/2003).

Bouwer, H. 2002. Integrated water management for the 21st century: Problems and solutions. *Journal of Irrigation and Drainage Engineering* 128(4): 193–202.

Brown, L.R. 2002. Water deficits growing in many countries: Water shortages may cause food shortages. Washington, D.C.: Earth Policy Institute. http://www.earth-policy.org/Updates/Update15.htm (8/6/2004).

Buros, O.K. 2000. The ABC's of Desalting. International Desalting Association: Topsfield, MA. http://www.idadesal.org/PDFS/Publications/ABCs.pdf (2/15/2003).

Cech TV. 2003. *Principles of Water Resources: History, Development, Management and Policy*. New York: John Wiley & Sons, Inc.

De Waal, C.S., L. Alderton, and M.J. Jacobson. 2000. Outbreak alert! Closing the gaps in our federal food-safety net. Washington, D.C.: Center for Science in the Public Interest.

Doll, P. 2002. Impact of climate change and variability on irrigation requirements: A global perspective. *Climate Change* 54: 269–293.

Downing, T.E. and M.L. Parry. 1994. Introduction: Climate change and world food security. *Food Policy* 19: 99–104.

Engelman, R. and P. LeRoy. 1993. Conserving Land: Population and Sustainable Food Production. Washington, D.C.: Population Action International.

EPA. 2002. National Management Measures to Control Nonpoint Source Pollution from Agriculture. Washington, D.C.: Office of Wetlands, Oceans, Watersheds, December 12th 2002, Environmental Protection Agency.

Falkenmark, M. 1995. Land and water linkages: A synopsis. *Proceedings of an Informal FAO Workshop on Land and Water Integration and River Basin Management*; 31 January–2 February 1993. Rome, Italy. FAO Land and Water Bulletin I. pp. 15–17.

Falkenmark, M. and G. Lindh. 1993. Water and economic development. In P. Gleick (ed.), *Water in Crisis: A Guide to the World's Fresh Water Resources*, pp. 80–91. Oxford, UK: Oxford University Press.

FAO. 1998. Food Balance Sheets. http://armanncorn:98ivysub@faostat.fao.org/lim...ap.pl? (9/24/2000).

FAO. 2000. New dimensions in water security: Society and ecosystem services in the 21st century. J. Lundqvist (ed.) with M. Falkenmark, L. Gordon, C. Folke, and L Ohlsson. FAO, *Land and Water Development Division*. Rome, Italy. ftp://ftp.fao.org/agl/aglw/docs/misc25.pdf (1/31/2003).

FAO. 1961–2002. World Grain Production. 1961–2002. Food and Agriculture Organization, United Nations. Quarterly Bulletin of Statistics. Rome, Italy.

FAO. 2002. Crops and Drops: Making the Best Use of Water for Agriculture. Food and Agriculture Organization, United Nations, Rome, Italy. http://www.fao.org/DOCREP/005/Y3918E/Y3918E00.HTM (12/8/2002).

Fattig, P. 2001. Debating a Diversion. http://www.mailtribune.com/archive/2001/april/042201n1.htm (12/8/2002).

GEF. 2002. The Challenge of Sustainability. Global Environment Facility. Washington, D.C. http://www.gefweb.org/Outreach/outreach-Publications/MainBook.pdf (2/14/2003).

Gleick, P.H. 1993. *Water in Crisis*. New York: Oxford University Press.

Gleick, P.H. 2000. *The World's Water*. Washington, D.C.: Island Press.

Gleick, P.H. 2002. Soft water paths. *Nature* 418(6896): 373.

Gleick, P.H. 2004. Global freshwater resources: Soft-path solutions for the 21st century. *Science* 302: 1524–1528.

Gleick, P.H, E.L. Wolff, and R.R. Chalecki. 2002. The New Economy of Water: The Risks and Benefits of Globalization and Privatization of Freshwater. Oakland, CA: Pacific Institute for Studies in Development, Environment, and Security. 48 pp.

Glenn, E.P., A. Zamora-Arroyo, P.L. Nagler, et al. 2001. Ecology and conservation biology of the Colorado River Delta, Mexico. *Journal of Arid Environments* 49: 5–15.

Guenette, M. 2001. Measurements of Water Erosion and Infiltration in Alberta Using a Rainfall Simulator. http://www.agric.gov.ab.ca/sustain/rainfall2.html (12/8/2002).

Havera, S.P., L.B. Suloway, and J.E. Hoffman. 1997. Wetlands in the Midwest with special reference to Illinois. In M.W. Schwartz (ed.), *Conservation in Highly Fragmented Landscapes*, pp. 88–104. New York: Chapman & Hall.

Hinrichsen, D., B. Robey, and U.D. Upadhyay. 1998. Solutions for a water-short world. Population Reports series M. no. 14. Baltimore, MD: Johns Hopkins School of Public Health, Population Information Program.

Hotez, P.J., J.M. Hawdon, M. Cappello, et al. 1996. Molecular approaches to vaccinating against hookworm disease. *Pediatric Research* 40: 515–521.

Howarth, R.W. 2003. The history and current status of eutrophication in freshwater and marine ecosystems. Aquatic Sciences Meeting. http://www.sgmeet.com/aslo/slc2003/sessionschedule.asp?SessionID=SS1.05 (2/6/2004).

IPCC. 2002. *Intergovernmental Panel on Climate Change. Climate Change 2001: Impacts, Adaptation, and Vulnerability*. Cambridge, UK: Cambridge University Press.

IRZ. 2002. Water Conservation. http://www.irz.com/IRZ/pages/conservation.htm (3/2/2003).

Knowles, N. and D.R. Cayan. 2003. Potential effects of global warming on the Sacramento/San Joaquin watershed and the San Francisco estuary. *Geophysical Research Letters* 29: 38-1–38-4.

Lal, R. 1993. Soil erosion and conservation in West Africa. In D. Pimentel (ed.), *World Soil Erosion and Conservation*, pp. 7–26. Cambridge, UK: Cambridge University Press.

Murphy, D.E. 2003. In a First, U.S. Puts Limits on California's Thirst. *The New York Times*. National Sunday, January 5, 2003. p. 1, 16.

Myers, N. and J. Kent. 2001. *Perverse Subsidies: How Tax Dollars Can Undercut the Environment and the Economy*. Washington, D.C.: Island Press.

NAS. 2003. *Frontiers in Agricultural Research: Food, Health, Environment, and Communities*. Washington, D.C.: National Academy of Science Press.

NGS. 1995. *Water: A Story of Hope*. Washington, D.C.: National Geographic Society.

Parry, M.L. and T.R. Carter. 1989. The impact of climate change on agriculture. In I.C. Topping (ed.), *Proceedings Second North American Conference on Preparing for Climate Change*, pp. 180–184. Washington, D.C.: Climate Institute.

Pimentel, D., B. Berger, D. Filiberto, et al. 2004. Water Resources, Agriculture, and the Environment. Environmental Biology, Report No. 04-1. New York State College of Agriculture and Life Sciences.

Postel, S. 1999. *Pillar of Sand: Can the Irrigation Miracle Last?* New York: W.W. Norton.

Postel, S.L., G.C. Daily, and P.R. Ehrlich. 1996. Human appropriation of renewable fresh water. *Science* 271: 785–787.

PRB. 2003. *World Population Data Sheet*. Washington, D.C.: Population Reference Bureau.

Pugh, C.A. 2001. Improving Irrigation Operations to Restore In-Stream Flows. U.S. Bureau of Reclamation, Water Resources Laboratory, Denver, CO. http://www.iahr.org/membersonly/grazproceedings99/doc/000/000/192.htm (2/21/2003).

Richter, E.D. 2002. Acute human pesticide poisonings. In D. Pimentel (ed.), *Encyclopedia of Pest Management*, pp. 3–6. New York: Marcel Dekker.

Root, T.L., J.T. Price, K.R. Hall, et al. 2003. Fingerprints of global warming on wild animals and plants. *Nature* 421(2): 57–60.

Rosengrant, M.K., X. Cai, and S.A. Cline. 2002. *World Water and Food to 2025*. Washington, D.C.: International Food Policy Research Institute.

Schalch, K. 2003. Providing Safe Drinking Water to Developing Nations. Transcript. http://www.unesco.org/water/wwap/news/national_public_radio.shtml (4/6/2003).

Shiklomanov, I.A. 1993. World fresh water resources. In P. Gleick (ed.), *Water in Crisis: A Guide to the World's Fresh Water Resources*, pp. 13–24. Oxford, UK: Oxford University Press.

Shiklomanov, I.A. and J.C. Rodda. 2003. *World Water Resources at the Beginning of the Twenty-First Century*. Cambridge, UK: Cambridge University Press.

Snell, A. 1997. The Effect of Windbreaks on Crop Growth in the Atherton Tablelands of North Queensland. Rural Industries Research and Development Corporation. RIROC. http://www.rirdc.gov.au/pub/shortreps/sr67.html (3/3/2004).

Solley, W.B., R.R. Pierce, and H.A. Perlman. 1998. Estimated Use of Water in the United States in 1995. Washington, D.C.: U.S. Geological Survey. Circular 1200.

Tuijl, W. van. 1993. *Improving Water Use in Agriculture: Experience in the Middle East and North Africa*. Washington, D.C.: World Bank.

UN. 2001. UN Population Division issues. World Population Prospects: The 2000 Revision. UN Press Release, DEV/2292, POP/791 (27/02/2001).

UN. 2002. Meeting Basic Needs. UN World Water Development Report. Facts and Figures. United Nations World Water Assessment Programme.

UNEP. 2003a. Water scarcity in the Middle East-North African Region. http://www.skmun.freeservers.com/unep/unepres1.htm (1/20/2003).

UNEP. 2003b. Global Environment Outlook 3: Past, Present and Future Perspectives. United Nations Environment Programme. London: Earthscan Publications Ltd.

UNESCO. 2001a. Securing the Food Supply. World Water Assessment Programme. United Nations Education Scientific and Cultural Organization, Paris.

UNESCO. 2001b. Managing Risks. World Water Assessment Programme. United Nations Education Scientific and Cultural Organization, Paris.

UNESCO. 2001c. Valuing Water. World Water Assessment Programme. United Nations Education Scientific and Cultural Organization, Paris.

UNESCO. 2001d. Sharing Water Resources. World Water Assessment Programme. United Nations Education Scientific and Cultural Organization, Paris.

USBC. 2003. Statistical Abstract of the United States. 2003. Washington, D.C.: U.S. Bureau of the Census, U.S. Government Printing Office.

USDA. 2003. Agricultural Statistics. U.S. Department of Agriculture. Washington, D.C.: U.S. Government Printing Office.

USDI. 2001. Quality of Water: Colorado River Basin. Progress Report No. 20. July 2001. U.S. Department of Interior. Washington, D.C.: U.S. Government Printing Office. 92 pp.

USGS. 2003a. Water use. U.S. Geological Survey. http://wwwga.usgs.gov/edu/wugw.html (2/2/2003).

USGS. 2003b. Water Q & A: Water Use. U.S. Geological Survey. http://water.usgs.gov/droplet/qausage.html (2/21/2003).

VanBeers, C. and A. de Moor. 2001. *Public Subsidies and Policy Failures: How Subsidies Distort the Natural Environment, Equity and Trade, and How to Reform Them.* Northampton, MA: Edward Elgar Publisher.

Wallace, J.S. 2000. Increasing agricultural water use efficiency in meet future food production. *Agriculture, Ecosystems and Environment* 82(2000): 105–119.

WHO. 1992. Our Planet, Our Health: Report of the WHO Commission on Health and Environment. Geneva: World Health Organization.

WHO. 2002. The World Health Report. World Health Organization. http://www.who.int/whr/2002/chapter4/en/index3.html (12/13/2003).

WHO. 2004a. Women's Health in South-East Asia. http://w3.whosea.org/women2/ (2/6/2004).

WHO. 2004b. Water Sanitation and Health. World Health Organization. http://www.who.int/entity/water_sanitation_health/diseases/malnutrition/en (2/2/2004).

World Bank. 2003. International Trends in Water Pricing and Use. http://wbln0018.worldbank.org/mna/mena,nsf34b224d37365b3f852567ee0068bd93/2421f467c2c02628525695100666e9/$FILE/Rivadh-Final.ppt (4/4/2003).

15 Soil Erosion: A Food and Environmental Threat

The loss of soil from land surfaces by erosion is widespread globally and adversely affects the productivity of all natural ecosystems as well as agricultural, forest, and rangeland ecosystems (Lal and Stewart, 1990; Pimentel, 1993; Pimentel et al., 1995; Pimentel and Kounang, 1998). Concurrent with the escalating human population, soil erosion, water availability, energy, and loss of biodiversity rank as the prime environmental problems throughout the world.

Future world populations will require ever-increasing food supplies. Consider that more than 99.7% of human food comes from the land (FAO, 1998), while less than 0.3% comes from oceans and other aquatic ecosystems. Maintaining and augmenting the world food supply basically depends on the productivity and quality of all soils.

The changes inflicted on soils by human-induced erosion over many years are significant and have resulted in valuable land becoming unproductive and often eventually abandoned (Pimentel et al., 1995; Young, 1998). Simply put, soil erosion diminishes soil quality and thereby reduces the productivity of natural, agricultural, and forest ecosystems (Pimentel and Kounang, 1998; Pimentel, 2001). In addition, the valuable diversity of plants, animals, and microbes in the soil is damaged (Pimentel et al., 1995).

In this study, the diverse factors that cause soil erosion are evaluated. The extent of damage associated with soil erosion is analyzed, with emphasis on the impact these may have on future human food security as well as the natural environment.

CAUSES OF EROSION

Erosion occurs when soil is left exposed to rain or wind energy. Raindrops hit exposed soil with great energy and easily dislodge the soil particles from the surface. In this way, raindrops remove a thin film of soil from the land surface and create what is termed *sheet* erosion. This erosion is the dominant form of soil degradation (Troeh et al., 1991; Oldeman, 1997). The impact of soil erosion is intensified on sloping land, where often more than half of the surface soil is carried away as the water splashes downhill into valleys and waterways.

Wind energy also has great power to dislodge surface soil particles, and transport them great distances. A dramatic example of this was the wind erosion in Kansas during the winter of 1995–1996, when it was relatively dry and windy. Then approximately 65 t/ha was eroded from this valuable cropland during one winter (Figure 15.1). Wind energy is strong enough to propel soil particles thousands of miles. This is illustrated in the photograph by NASA (Figure 15.2) which shows a cloud of soil being blown from the African Continent to the South and North American continents.

FIGURE 15.1 About 50 mm of soil blown from cropland in Kansas during the winter of 1995–1996. (E.L. Skidmore, USDA, Manhattan, KS. Photo, spring 1996.)

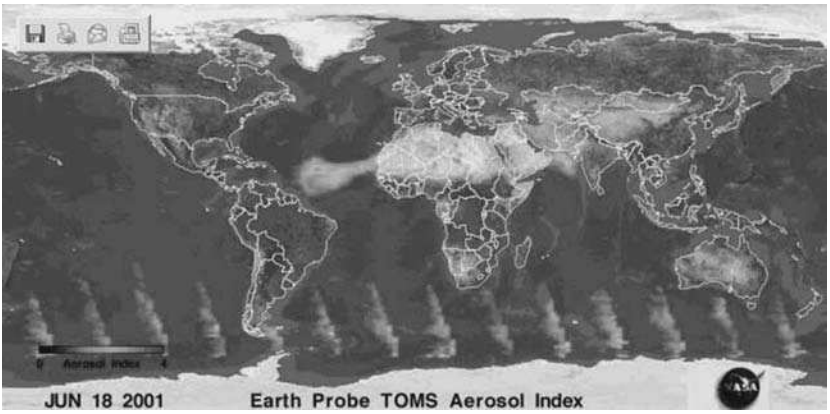

FIGURE 15.2 Cloud of soil from Africa being blown across the Atlantic Ocean. (Imagery by SeaWIFS Project, NASA/Goddard Space Flight Center and ORBIMAGE, 2000.)

SOIL STRUCTURE

Soil structure influences the ease with which it can be eroded. Soils with medium to fine texture, low organic matter content, and weak structural development are most easily eroded (Bajracharya and Lal, 1992). Typically these soils have low water infiltration rates and, therefore, are subject to high rates of water erosion and the soil particles are easily displaced by wind energy.

THE ROLE OF VEGETATIVE COVER

Land areas covered by plant biomass, living or dead, are more protected and experience relatively little soil erosion because raindrop and wind energy are dissipated by the biomass layer and the topsoil is held by the biomass (SWAG, 2002; Agriculture California, 2002). For example, in Utah and Montana, as the amount of ground cover decreased from 100% to less than 1%, erosion rates increased approximately 200 times (Trimble and Mendel, 1995).

In forested areas, a minimum of 60% forest cover is necessary to prevent serious soil erosion and landslides (Singh and Kaur, 1989; Haigh et al., 1995; Forest Conservation Act, 2002). The extensive removal of forests for crops and pastures is followed by extensive soil erosion.

Loss of soil vegetative cover is especially widespread in developing countries where populations are large, and agricultural practices are often inadequate to protect topsoils. In addition, cooking and heating there frequently depends on the burning of harvested crop residues for fuel. For example, about 60% of crop residues in China and 90% in Bangladesh routinely are stripped from the land and burned for fuel (Wen, 1993). In areas where fuelwood and other biomass are scarce, even the roots of grasses and shrubs are collected and burned (McLaughlin, 1991). All these practices leave the soil barren and fully exposed to rain and wind forces of erosion.

LAND TOPOGRAPHY

The topography of a given landscape, its rainfall or wind and exposure all combine to influence its susceptibility to erosion. In the Philippines, where more than 58% of the land has a slope of greater than 11%, and in Jamaica, where 52% of the land has a slope greater than 20%, soil erosion rates as high as 400 t/ha/year have been reported (Lal and Stewart, 1990). Erosion rates are high especially on marginal and steep lands that have been converted from forests to agriculture to replace the already eroded, unproductive cropland (Lal and Stewart, 1990). In addition, under arid conditions and with relatively strong winds as much as 5600 t/ha/year of soil has been reported lost in an arid region of India (Gupta and Raina, 1996).

OTHER SOIL DISTURBANCES

Although world agricultural production accounts for about three-quarters of the soil erosion worldwide, erosion also occurs whenever humans remove vegetative cover (Lal and Stewart, 1990; FAO, 2002). The construction of roads, parking lots, and buildings are examples of this problem. Although the rate of erosion from construction sites may range from 20 to 500 t/ha/year, erosion associated with construction especially is relatively brief, generally lasting only while the land surface is disturbed. Then once the land surface is seeded to grass or vegetation regrows naturally, erosion decreases (IECA, 1991). However, if the soil remains covered by buildings, parking lots, and roads, the area is lost for vegetation production and water runoff in adjacent areas increases.

Natural ecosystems also suffer erosion losses. This is especially evident along stream banks, where erosion occurs naturally from the powerful action of adjacent moving water. Increased soil losses occur on steep slopes (30% or more), when a stream cuts through adjacent land. Even on relatively flat land with only a 2% slope, streambanks are eroded, especially during heavy rains and flooding. There too, the presence of cattle in and around streams further increases streambank erosion. For example, a Wisconsin stream area inhabited by cattle lost about 60 t/year of soil along each kilometer of stream length (Trimble, 1994; Trimble and Mendel, 1995).

Soil erosion accompanies landslides and earthquakes (Bruijnzeel, 1990; McTainish and Boughton, 1993). Landslides, in which layers of soil are dislodged and move downhill, usually are associated with diverse human activities, such as the construction of roads and buildings, and the removal of forests. Overall, the erosion impact from earthquakes is comparatively minimal mainly because these events are relatively rare. However, when earthquakes occur, massive amounts of soil, including crops and forests, are affected in hillsides and in surrounding areas.

ASSESSING SOIL EROSION

Although soil erosion has been taking place very slowly in natural ecosystems throughout geologic time, its cumulative impacts on soil quality over billions of years have been significant. Worldwide, erosion rates range from a low of 0.001 to 2 t/ha/year on relatively flat land with grass or forest cover to rates ranging from 1 to 5 t/ha/year in mountainous regions with normal vegetative cover (Patric, 2002). Yet, even low rates of erosion sustained over billions of years result in the displacement of enormous quantities of soil. For example, over a period of 100 years at an erosion loss rate of 2 t/ha/year on 10 ha, erosion will deposit the soil equivalent of about 1 ha of land with a soil depth of 15 cm. In addition, eroded soil frequently accumulates in valleys forming vast alluvial plains. The large deltas of the world, such as those of the Nile and the Mississippi, are the result of centuries of erosion (Solliday, 1997).

Myers (1993) reports that approximately 75 billion tons of fertile soil are lost from world agricultural systems each year, with much less erosion occurring in natural ecosystems. In fact, the 75 billion tons is probably a conservative value. Soil scientists Lal and Stewart (1990) and Wen (1997) report 6.6 billion tons of soil per year are lost in India and 5.5 billion tons are lost annually in China. Considering these two countries together occupy only 13% of the world's total land area, the estimated 75 billion tons of soil lost per year worldwide is conservative. The amount of soil lost in the United States is estimated to be about 3 billion tons per year (Carnell, 2001).

LOSS OF PRODUCTIVITY IN MANAGED ECOSYSTEMS

Approximately 50% of the Earth's land surface is devoted to agriculture; of this, about one-third is used for crops and two-thirds as grazing lands (USDA, 2001). Forests occupy about 20% of the land area (WRI, 1997). Of these two areas, cropland is more susceptible to erosion because of frequent cultivation of the soils and the vegetation is often removed before crops are planted. This practice exposes the soil to wind and rain energy. In addition, cropland is often left without vegetation between plantings. This practice intensifies erosion on agricultural land, which is estimated to be 75 times greater than erosion in natural forest areas (Myers, 1993).

WORLDWIDE CROPLAND

Currently, about 80% of the world's agricultural land suffers moderate to severe erosion, while 10% experiences slight erosion (Pimentel, 1993; Speth, 1994; Lal, 1994). Worldwide, erosion on cropland averages about 30 t/ha/year and ranges from 0.5 to 400 t/ha/year (Pimentel et al., 1995). As a result of soil erosion, during the last 40 years about 30% of the world's arable land has become unproductive and much of that has been abandoned for agricultural use (WRI, 1994; Kendall and Pimentel, 1994).

The nearly 1.5 billion ha of world arable land now under cultivation for crop production are almost equal in area to the amount of arable land (2 billion ha) that has been abandoned by humans since farming began (Lal, 1990, 1994). Such land, once biologically and economically productive, now not only produces little biomass but also has lost considerable diversity of the plants, animals, and microbes that it once supported (Pimentel et al., 1992; Heywood, 1995).

Each year an estimated 10 million ha of cropland worldwide are abandoned due to lack of productivity caused by soil erosion (Faeth and Crosson, 1994). Worldwide, soil erosion losses are highest in the agroecosystems of Asia, Africa, and South America, averaging 30–40 t/ha/year of soil loss (Taddese, 2001). In developing countries, soil erosion is particularly severe on small farms that are often located on marginal lands where the soil quality is poor and the topography is frequently steep. In addition, the poor farmers tend to raise row crops, such as corn. Row crops are highly susceptible to erosion because the vegetation does not cover the entire soil surface (Southgate and Whitaker, 1992; Stone and Moore, 1997). For example, in the Sierra Region of Ecuador, 60% of the cropland was abandoned because erosion and inappropriate agricultural practices left the land devastated by water and wind erosion (Southgate and Whitaker, 1992). Similar problems are evident in the Amazonian region of South America, especially where vast forested areas are being cleared to provide more land for crops and livestock production.

U.S. CROPLAND

The lowest erosion rates on cropland occur in the United States and Europe where they average about 10 t/ha/year (USDA, 2000a,b). However, these low rates of erosion greatly exceed the average rate of natural soil formation from the parent material; under agricultural conditions that range from 0.5 to 1 t/ha/year (Troeh and Thompson, 1993; Lal, 1994; Pimentel et al., 1995; Young, 1998; Sundquist, 2000).

This means that 90% of U.S. cropland is now losing soil faster than its sustainable replacement rate (USDA, 2000a,b).

Soil erosion is severe in some of the most productive agricultural ecosystems in the United States. For instance, one-half of the fertile topsoil of Iowa has been lost by erosion during the last 150 years of farming because of erosion (Risser, 1981; Klee, 1991). These high rates of erosion continue there at a rate of about 30 t/ha/year, because of the rolling topography and type of agriculture practiced (USDA, 1989). Similarly, 40% of the rich soil of the Palouse region in the northwestern United States has been lost during the past 100 years of cultivation (Ebbert and Roe, 1998). In both these regions, intensive agriculture is employed and mono-cultural plantings are common. Also, many of these fields are left unplanted during the late fall and winter months, further exposing the soil to erosion. Yearly in the United States, several thousand hectares of valuable cropland are abandoned because rain and wind erosion has made them unproductive (World Problems, 1999).

The economic impact of soil erosion is significant. Uri (2001) estimates that soil erosion in the United States costs the nation about $37.6 billion each year in loss of productivity.

PASTURE AND RANGE LAND

In contrast to the average soil loss of 10 t/ha/year from U.S. cropland, U.S. pastures lose about 6 t/ha/year (NAS, 2003). However, erosion rates on pastures intensify whenever overgrazing is allowed to occur on the pastures. Even in the United States, about 75% of non-Federal lands require conservation treatments to improve grazing pressures (Johnson, 1995). More than half of the rangelands, including those on non-Federal and Federal lands, are now overgrazed and have become subject to high erosion rates (Bailey, 1996; Campbell, 1998).

Although erosion rates on U.S. cropland have decreased during the past two decades, erosion rates on rangelands remain relatively high or about 6 t/ha/year (NAS, 2003). High erosion rates are typical on more than half of the world's rangelands (WRI, 1994). In many developing countries, heavy grazing by sheep and goats has removed most of the vegetative cover, exposing the soil to severe erosion. In Africa, about 80% of the pasture and rangeland areas are seriously eroded and degraded by soil erosion (UN-NADAF, 1996). The prime causes of this are overgrazing and the practice of removing crop residues for cooking fuel.

FOREST LAND

In stable forest ecosystems, where soil is protected by vegetation, erosion rates are relatively low, ranging from only 0.004 to 0.05 t/ha/year (Roose, 1988; Lal, 1994). Tree leaves and branches not only intercept and diminish rain and wind energy, but also cover the soil under the trees to further protect the soil. However, this changes dramatically when forests are cleared for crop production or pasture (Daily, 1996). For example, in Ecuador, the Ministry of Agriculture and Livestock reported that 84% of the soils in the hilly, forested northeastern part of the country should never have been cleared for pastures because of the high vulnerability of the soils to erosion, their limited fertility, and the overall poor soil type that resulted (Southgate and Whitaker, 1992).

EFFECTS OF EROSION ON TERRESTRIAL ECOSYSTEMS

Soil erosion reduces the productivity of terrestrial ecosystems. In order of importance, soil erosion increases water runoff thereby decreasing the water infiltration and the water-storage capacity of the soil (Troeh et al., 1991; Pimentel et al., 1995; Jones et al., 1997). Also, during the erosion process organic matter and essential plant nutrients are removed from the soil and the soil depth is reduced. These changes not only inhibit vegetative growth, but reduce the presence of valuable biota and the overall biodiversity in the soil (Troeh et al., 1991; Pimentel et al., 1995). As these factors interact with one another, it is almost impossible to separate the specific impacts of one factor from another. For example, the loss of soil organic matter increases water runoff, which reduces water-storage capacity, which diminishes nutrient levels in the soil and also reduces the natural biota biomass and the biodiversity of ecosystems (Lal and Stewart, 1990; Jones et al., 1997).

WATER AVAILABILITY

Water is a prime limiting factor of productivity in all terrestrial ecosystems because all vegetation requires enormous quantities of water for its growth and for the production of fruit (Falkenmark, 1989; Pimentel et al., 1997). For instance, 1 ha of corn or wheat will transpire more than 5–7 million L of water each growing season (Klocke et al., 1996; Pimentel et al., 1997) and lose an additional 2 million L of water by evaporation from the soil (Donahue et al., 1990; Pimentel et al., 1997). During erosion by rainfall, the amount of water runoff significantly increases, with less water entering the soil, and less water available to support the growing vegetation.

In contrast to uneroded soils, moderately eroded soils absorb from 10 to 300 mm less water per hectare per year from rainfall. This represents a decrease of 7%–44% in the amount of water available for vegetation growth (Wendt et al., 1986; Murphee and McGregor, 1991). A water runoff rate of about 30% of total rainfall of 800 mm can result in significant water shortages for crops, like corn, and ultimately low crop yields.

When soil water availability for an agricultural ecosystem is reduced from 20% to 40% in the soil, plant biomass productivity is reduced from 10% to 25% depending also on total rainfall, soil type, slope, and other factors (Evans et al., 1997). Major reductions in plant biomass not only diminish crop yields, but adversely affect the overall species diversity within the ecosystem (Heywood, 1995; Walsh and Rowe, 2001).

NUTRIENT LOSS

Eroded soil carries away vital plant nutrients such as nitrogen, phosphorus, potassium, and calcium. Typically, eroding soil contains about three times more nutrients than are left in the remaining soil (Young, 1989). A ton of fertile topsoil averages 1–6 kg of nitrogen, 1–3 kg of phosphorus, and 2–30 kg of potassium, whereas the soil on eroded land has average nitrogen levels of only 0.1–0.5 kg/t (Troeh et al., 1991).

When nutrient resources are so depleted by erosion, plant growth is stunted and overall productivity declines (Lal and Stewart, 1990; Pimentel et al., 1995). Nutrient deficient soils produce 15%–30% lower crop yields than uneroded soils (Olson and Nizeyimana, 1988; Schertz et al., 1989; Langdale et al., 1992).

To offset the nutrient losses erosion inflicts on crop production, large quantities of fertilizers are often applied. Troeh et al. (1991) estimate that the lost soil nutrients cost U.S. agriculture $20 billion annually. If the soil base is relatively deep, about 300 mm, and if only from 10 to 20 t of soil are lost per hectare per year, the lost nutrients can be replaced with the application of commercial fertilizers or livestock manure (Pimentel et al., 1995). However, this replacement strategy is expensive for the farmer and nation and usually not affordable by poor farmers. Not only are the fertilizer inputs fossil-energy dependent, but these chemicals can also harm human health and pollute the environment (NAS, 2003).

Soil Organic Matter

Fertile soils typically contain about 100 tons of organic matter per hectare (or 4% of the total soil weight) (Follett et al., 1987; Young, 1990; Sundquist, 2000). About 95% of the soil nitrogen and 25%–50% of the phosphorus are contained in the soil organic matter (Allison, 1973). Because most of the soil organic matter is found close to the soil surface as decaying leaves and stems, erosion significantly decreases soil organic matter. Both wind and water erosion selectively remove the fine organic particles in the soil, leaving behind large soil particles and stones. Several studies have demonstrated that the soil removed by either erosion is 1.3–5 times richer in organic matter than the remaining soil left behind (Allison, 1973; Lal and Stewart, 1990). For example, the reduction of soil organic matter from 1.4% to 0.9% lowered the yield potential for grain by 50% (Libert, 1995; Sundquist, 2000).

Soil organic matter is a valuable resource because it facilitates the formation of soil aggregates and thereby increases soil porosity. The soil organic matter improves soil structure, which in turn facilitates water infiltration and ultimately the overall productivity of the soil (Langdale et al., 1992). In addition, organic matter aids cation exchange, enhances plant root growth, and stimulates the increase of important soil biota (Allison, 1973; Wardle et al., 2004).

Once the organic matter layer is depleted, the productivity of our ecosystem, as measured by plant biomass, declines both because of the degraded soil structure and the depletion of nutrients contained in the organic matter. In addition to low yields, the total biomass of the biota and overall biodiversity of these ecosystems are substantially reduced (Heywood, 1995; Walsh and Rowe, 2001; Lazaroff, 2001).

Collectively and independently the diverse impacts of erosion reduce crop biomass, both because of degraded soil structure and nutrient depletion. For example, erosion reduced corn productivity by 9%–18% in Indiana, 0%–24% in Illinois and Indiana, 25%–65% in the southern Piedmont of Georgia, and 21% in Michigan (Olson and Nizeyimana, 1988; Mokma and Sietz, 1992; Weesies et al., 1994). In the Philippines over the past 15 years, erosion caused declines in corn production by as much as 80% (Dregne, 1992).

Soil Depth

Growing plants require soils of adequate depth in which to extend their roots. Various soil biota, like earthworms, also require a specific soil depth (Pimentel et al., 1995; Wardle et al., 2004). Thus, when soil depth is substantially reduced by erosion from 30 cm to less than 1 cm, plant root space is minimal, and plant production is significantly reduced.

BIOMASS AND BIODIVERSITY

The biological diversity existing in any ecosystem is related directly to the amount of living and nonliving organic matter present in the ecosystem (Wright, 1990; Heywood, 1995; Walsh and Rowe, 2001; Lazaroff, 2001; Wardle et al., 2004). As mentioned, by diminishing soil organic matter and soil quality, erosion reduces overall biomass and productivity. Ultimately, this has a profound effect on the diversity of plants, animals, and microbes present in an entire ecosystem.

Numerous positive associations have been established between biomass abundance and species diversity (Elton, 1927; Odum, 1978; Sugden and Rands, 1990; M. Giampietro, 1997, personal communication, Insituto Nazionale della Nutrizione, Rome, Italy). Vegetation is the main component of ecosystem biomass and provides the vital resources required both by animals and microbes for their survival. This relationship is summarized in Table 15.1.

Along with plants and animals, microbes are a vital component of the soil and constitute a large percentage of the soil biomass. One square meter of soil may support about 200,000 arthropods and enchytraeids, plus billions of microbes (Wood, 1989; Lee and Foster, 1991). A hectare of productive soil may have a biomass of invertebrates and microbes weighing up to 10,000 kg/ha (Table 15.1). In addition, soil bacteria and fungi add 4000–5000 species and in this way contribute significantly to the biodiversity especially in moist, organic forest soils (Heywood, 1995).

Erosion rates that are 10–20 times above the sustainability rate (soil formation rates of less than 0.5 to 1 t/ha/year) decrease the diversity and abundance of soil organisms (Atlavinyte, 1965). In contrast, agricultural practices that control erosion and maintain adequate soil organic matter favor the proliferation of soil biota (Reid, 1985; FAO, 2001).

TABLE 15.1
Biomass of Various Organisms per Hectare in a Temperate Region Pasture (Pimentel et al., 1992)

Organism	Biomass (kg fresh weight)
Plants	20,000
Fungi	4,000
Bacteria	3,000
Arthropods	1,000
Annelids	1,320
Protozoa	380
Algae	200
Nematodes	120
Mammals	1.2
Birds	0.3

The application of organic matter or manure also enhances the biodiversity in soil (Agriculture Canada, 2002; IFPRI, 2002). Species diversity of macrofauna (mostly arthropods) increased by 16% when organic manure was added to experimental wheat plots in the former USSR (Bohac and Pokarzhevsky, 1987). Similarly, species diversity of macrofauna (mostly arthropods) more than doubled when organic manure was added to grassland plots in Japan (Kitazawa and Kitazawa, 1980), and increased 10-fold in Hungarian agricultural land (Olah-Zsupos and Helmeczi, 1987).

The relationship between biomass and biodiversity was confirmed in field experiments with collards (Brassicae) in which arthropod species diversity rose fourfold in the experimental plots with the highest collard biomass compared with that in control collard plots (Pimentel and Warneke, 1989). Reports suggest that when biomass was increased threefold, the number of species increased 16-fold (Ecology, 2002) In a study of bird populations, a strong correlation between plant biomass productivity and bird species diversity was reported when a 100-fold increase in plant biomass yielded a 10-fold increase in bird diversity (Wright, 1990).

Soil erosion has indirect effects on ecosystems that may be nearly as damaging as the direct effects of reducing plant biomass productivity. For example, Tilman and Downing (1994) found that the stability and biodiversity of grasslands were significantly decreased when plant species reduction occurred. They reported that as plant species richness decreased from 25 species to 5 or less species, the grassland became less resistant to drought. The total amount of biomass declined to one fourth of the high level. The overall result was that the grassland was more susceptible to drought conditions and required more time to recover its productivity than when an abundance of plant species was present.

Sometimes soil erosion causes the loss of a keystone species, and its absence may have a cascading effect on the survival of a wide array of other species within the ecosystem. Species that act as keystone species include the dominant plant types, such as oaks, that maintain the biomass productivity and integrity of the ecosystem; predators and parasites that control the feeding pressure of some organisms on major plants; pollinators of various vital plants in the ecosystem; seed dispersers; as well as the plants and animals that provide a habitat required by other essential species, like biological nitrogen-fixers (Heywood, 1995; Daily, 1996). Thus, in diverse ways, the normal activities within an ecosystem may be interrupted when populations of keystone species are significantly altered. The damages inflicted can be severe especially in agroecosystems when, for instance, the numbers of pollinators are drastically reduced or even eliminated and there is little or no reproduction in the plants (Pimentel et al., 1997).

Soil biota perform many beneficial activities that improve soil quality and ultimately its productivity (Witt, 1997; FAO, 2001; Sugden et al., 2004). For example, soil biota recycle basic nutrients required by plants for their growth (Pimentel et al., 1995). In addition, the tunneling and burrowing activities of earthworms and other soil biota enhance productivity by increasing water infiltration into the soil (Witt, 1997). Earthworms, for instance, may produce up to 220 tunnel openings per square meter (3–5 mm in diameter). These channels enable water to infiltrate rapidly into the soil (Anderson, 1988; Edwards and Bater, 1992).

Other soil biota also contribute to soil formation and productivity by mixing the soil components, enhancing aggregate stability, and preventing soil crusting.

This churning and mixing of the upper soil redistributes nutrients, aerates the soil, exposes soil to the climate for soil formation, and increases infiltration rates, thus making the soil favorable for increased soil formation and plant productivity. Earthworms bring between 10 and 500 t/ha/year of soil from underground to the soil surface (Lavelle, 1983; Lee, 1985), while some insects, like ants, may bring 34 t/ha/year of soil to the surface (Zacharias and Grube, 1984; Lockaby and Adams, 1985; Hawkins, 2002). In arid regions, species, like the Negev desert snail, *Euchordrus* spp., also help form soil by consuming lichens and the rocks on which the lichens are growing (Shachak et al., 1995). This snail activity helps form about 1000 kg of soil per hectare per year, which is equal to the annual soil formation rate by wind-borne deposits.

SEDIMENTS AND WIND BLOWN SOIL PARTICLES

Beyond damages to rainfed agricultural and forestry ecosystems, the effects of erosion reach far into surrounding environments (Gray and Leiser, 1989; FEMAT, 1993; Ziemer, 1998).

For instance, large amounts of eroded soil are deposited in streams, lakes, and other ecosystems. The USDA (1989) reports that 60% of the water-eroded soil ends up in U.S. streams. Similarly in China, approximately 2 billion t/year of soil are transported down the Yellow River in China into the Yellow Sea (Lal and Stewart, 1990; McLaughlin, 1993; Zhang et al., 1997). The most costly off-site damages occur when soil particles enter lake and river systems (Lal and Stewart, 1990; Martin, 1997; Watershed, 2002). Of the billions of tons of soil lost from the United States and world cropland, nearly two-thirds finally is deposited in lakes and rivers (USDA, 1989; Pimentel, 1997). In some areas, heavy sedimentation leads to river and lake flooding (Myers, 1993). For example, some of the flooding that occurred in the midwestern United States during the summer of 1993 was caused by increased sediment deposition in the Mississippi and Missouri Rivers and their tributaries. These deposits raised the waterways, making them more prone to overflowing and flooding (Allen, 1994). Sediments disrupt and harm aquatic ecosystems by contaminating the water with soil particles and the fertilizer and pesticide chemicals they contain (Clark, 1987). Siltation of reservoirs and dams reduces water storage, increases the maintenance cost of dams, and shortens the lifetime of reservoirs (Pimentel et al., 1995).

Wind-eroded soil also causes off-site damage because soil particles propelled by strong winds act as abrasives and air pollutants (WEI, 2002; Wind Particles, 2002). Estimates are that soil particles sandblast U.S. automobiles and buildings, and cause about $8 billion in damages each year (Huszar and Piper, 1985; SCS, 1993; Pimentel et al., 1995). A prime example of the environmental impact of wind erosion occurs in the United States, where wind erosion rates average 13 t/ha/year and sometimes reach as much as 56 t/ha/year (Pimentel and Kounang, 1998; Ecology Action, 2002). Yearly off-site erosion costs in New Mexico, including health and property damage, are estimated to reach $465 million (Huszar and Piper, 1985). The off-site damage from wind erosion in the United States is estimated to cost nearly $10 billion each year (Pimentel et al., 1995).

The long range transport of dust by wind has implications for health worldwide. Griffin et al. (2001) report that about 20 human infectious disease organisms, like anthrax and tuberculosis, are easily carried in the soil particles transported by the wind.

Soil erosion contributes to global warming, because CO_2 is added to the atmosphere when the enormous amounts of biomass carbon in the soil are oxidized (Phillips et al., 1993; Lal et al., 1999; Lal, 2001, 2004; Walsh and Rowe, 2001). One hectare of soil may contain about 100 t of organic matter or biomass. The subsequent oxidation and release of CO_2 into the atmosphere, as the soil organic matter oxidizes, along with other atmospheric pollutants contributes to the global warming problem (Phillips et al., 1993; Lal, 2004). In fact, a feedback mechanism may exist wherein increased global warming intensifies rainfall which, in turn, increases erosion and continues the cycle (Lal, 2002).

CONSERVATION TECHNOLOGIES AND RESEARCH

Estimates are that agricultural land degradation alone can be expected to depress world food production approximately 30% during the next 25-year period (Buringh, 1989) or 50-year period (Kendall and Pimentel, 1994). These forecasts emphasize the need to implement known soil conservation techniques. These techniques include the use of biomass mulches, crop rotations, no-till, ridge-till, added grass strips, shelterbelts, contour row-crop planting, and various combinations of these. Basically all of these techniques require keeping the land protected from wind and rainfall energy by using some form of vegetative cover on the land (Troeh et al., 1991; Pimentel, 1993; Pimentel et al., 1995).

In the United States, during the past decade, soil erosion rates on croplands have been reduced nearly 25% using various soil conservation technologies (USDA, 1989, 1994, 2000a,b). Yet, even with this decline, soil is still being lost on croplands 10 times above its sustainability rate (USDA, 2000a,b). Unfortunately, soil erosion rates on rangelands have not declined during this same decade and remain at about six times sustainability (NAS, 2003).

Soil erosion is known to affect water runoff, soil water-holding capacity, soil organic matter, nutrients, soil depth, and soil biota. All of these influence soil productivity in both natural and managed ecosystems. Little is known about the ecology of the interactions of the various soil factors and their interdependency (Lal and Stewart, 1990; Pimentel, 1993). The effects of soil erosion on the productivity of both natural and managed ecosystems require serious research to develop effective soil and water conservation measures. Farmers will need incentives to fully implement conservation methods.

PRODUCTIVE SOILS AND FOOD SECURITY

There is no doubt that soil erosion is a critical environmental problem throughout the world's terrestrial ecosystems. Erosion is a slow insidious process. Indeed 1 mm of soil, easily lost in just one rain or wind storm, is so minute that its loss goes unnoticed. Yet this loss of soil over a hectare of cropland amounts to 15 t/ha. Replenishing

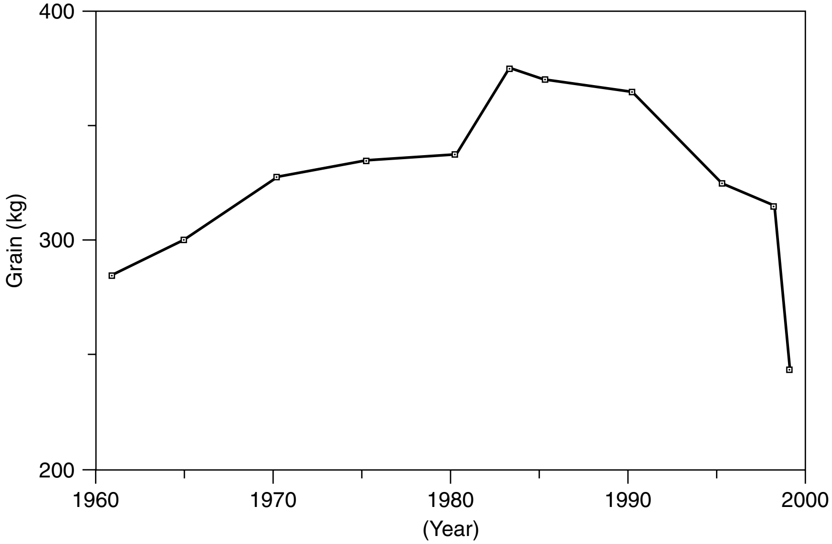

FIGURE 15.3 Cereal grain production per capita in the world from 1961 to 2000. (FAO, 1961–2000. *Quarterly Bulletin of Statistics*. 1–13.)

this amount of soil under agricultural conditions requires approximately 20 years, but meanwhile this soil is increasingly less able to support crop growth. Simultaneously, equally important losses of water, nutrients, soil organic matter, and soil biota are occurring. Forest, rangeland, and natural ecosystems are harmed when soil loss is ignored.

Concerning future food security, where cropland degradation is allowed to occur, crop productivity is significantly reduced. Shortages of cropland are already having negative impacts on world food production (Brown, 1997). For example, the Food and Agricultural Organization (FAO) of the United Nations reports that the availability of food per capita has been declining for nearly two decades, based on available cereal grains FAO (1961–2000) (Figure 15.3). Cereal grains make up 80%–90% of the world's food. Although grain yields per hectare in both developed and developing countries are still increasing, these increases are slowing while the world population continues to escalate. Now, and in the future decades, crop yields must be shared with more and more people (FAO, 1961–2000; PRB, 2002).

Worldwide, soil erosion continues unabated while the human population and its requirements for food, fiber, and other resources expand geometrically. Indeed, achieving future food security for all people depends on conserving fertile soil, water, energy, and biological resources. Careful management of all of these vital resources deserve high priority to ensure the effective protection of our agricultural and natural ecosystems. If conservation is ignored, the 3.7 billion malnourished people in the world will grow and per capita food production will decline further (WHO, 2004).

REFERENCES

Agriculture California. 2002. Control of soil erosion. http.//res2.agr.ca/ecorc/program3/pub/status/control.htm (10/8/2002).

Agriculture Canada. 2002. Range management. http://www/agr.gc.ca/pfra/land/range.htm (10/8/2002).

Allen, W. 1994. The flood of 1993 may rank as the worst weather disaster in U.S. history. *St. Louis Post Dispatch*, p. 01B.

Allison, F.E. 1973. *Soil Organic Matter and Its Role in Crop Production*. New York: Elsevier.

Anderson, J.M. 1988. Spatiotemporal effects of invertebrates on soil processes. *Biology and Fertility of Soils* 6: 216–227.

Atlavinyte, O. 1965. The effect of erosion on the population of earthworms (Lumbricidae) in soils under different crops. *Pedobiologia* 5: 178–188.

Bailey, A.W. 1996. Managing Canadian rangelands as a sustainable resource: Policy issues. Rangelands in a sustainable biosphere. Proceedings of the Fifth International Rangeland Congress, Salt Lake City, Utah, USA, 23–28 July, 1995. Volume 2: Invited Presentations. 5–7.

Bajracharya, R.M. and R. Lal. 1992. Seasonal soil loss and erodibility variation on a Miamian silt loam soil. *Soil Science Society of America Journal* 56(5): 1560–1565.

Bohac, J. and A. Pokarzhevsky. 1987. Effect of manure and NPK on soil macrofauna in chernozem soil. In J. Szegi (ed.), *Soil Biology and Conservation of Biosphere*, pp. 15–19. Proceedings of the 9th International Symposium. Budapest, Hungary: Akademiai Kiado.

Brown, L.R. 1997. *The Agricultural Link: How Environmental Deterioration Could Disrupt Economic Progress*. Washington, D.C.: Worldwatch Institute.

Bruijnzeel, L.A. 1990. *Hydrology of Moist Tropical Forests and Effects of Conversion: A State of Knowledge Review*. Amsterdam: Free University and UNESCO.

Buringh, P. 1989. Availability of agricultural land for crop and livestock production. In D. Pimentel and C.W. Hall (eds.), *Food and Natural Resources*, pp. 70–85. San Diego, CA: Academic Press, Inc.

Campbell, L.C. 1998. Managing soil fertility decline. *Journal of Crop Production* 1(2): 29–52.

Carnell, B. 2001. Soil erosion. http://www.overpopulation.com/fag/natural_resources/food/soil_erosion.html (12/17/2002).

Clark, E.H. 1987. Soil erosion: Offsite environmental effects. In J.M. Harlin and G.M. Bernardi (eds.), *Soil Loss: Processes, Policies, and Prospects*, pp. 59–89. New York: Westview.

Daily, G. 1996. *Nature's Services: Societal Dependence on Natural Ecosystems*. Washington, D.C.: Island Press.

Donahue, R.H., R.H. Follett, and R.N. Tulloch. 1990. *Our Soils and Their Management*. Danville, IL: Interstate Pub. Inc.

Dregne, H.E. 1992. Erosion and soil productivity in Asia. *Journal of Soil Water Conservation* 47: 8–13.

Ebbert, J.C. and R.D. Roe. 1998. Soil erosion in the Palouse River basin: Indications of improvement. Science for a Changing World, U.S. Geological Survey. USGS Fact Sheet FS-069-98.

Ecology. 2002. Biodiversity, productivity, and overyielding. http://web.utk.edu/~cuixu/School/ecology_debate/biodiversity.htm (12/17/2002).

Ecology Action. 2002. Soil. http://www.growbilointensive.org/biointensive/soil.html (2/17/2002).

Edwards, C.A. and J.E. Bater. 1992. The use of earthworms in environmental management. *Soil Biology and Biochemistry* 24: 1683–1689.

Elton, C.S. 1927. *Animal Ecology*. London: Sidgwick and Jackson.

Evans, R., D.K. Cassel, and R.E. Sneed. 1997. Soil, water, and crop characteristic important to irrigation scheduling. http://www.bae.ncsu.edu/programs/extension/evans/ag452-1.html (12/17/2002).

Faeth, P. and P. Crosson. 1994. Building the case for sustainable agriculture. *Environment* 36(1): 16–20.

Falkenmark, M. 1989. Water scarcity and food production. In D. Pimentel and C.W. Hall (eds.), *Food and Natural Resources*, pp. 164–191. San Diego, CA: Academic Press.

FAO. 1961–2000. *Quarterly Bulletin of Statistics*. FAO Quarterly Bulletin of Statistics 1–13: 125 pp.

FAO. 1998. Food Balance Sheet. http://armanncorn:98ivysub@faostat.fao.org/lim...ap.pl (10/12/2000).

FAO. 2001. Soil. Food and Agriculture Organization, United Nations. http://www.fao.org/ag/AGL/agll/soilbiod/casecall.htm (10/8/2002).

FAO. 2002. Restoring the land. http://www.fao.org/inpho/vlibrary/u8480e/U8480E0d.htm (12/17/2002).

FEMAT. 1993. Forest ecosystem management assessment team report. Sponsored by the USDA Forest Service, U.S. Environmental Protection Agency, USDOI Bureau of Land Management, National Park Service, Portland, OR.

Follett, R.F., S.C. Gupta, and P.G. Hunt. 1987. Conservation practices: Relation to the management of plant nutrients for crop production. In *Soil Fertility and Organic Matter as Critical Components of Production Systems, Special Pub. 19*, pp. 19–51. Madison, WI: Soil Science Society of America and American Society of Agronomy.

Forest Conservation Act. 2002. Riparian Forest Buffer Panel (Bay Area Regulatory Programs). www.riparianbuffers.umd.edu/manuals/regulatory.html+60%25+forest+soil+conservation&hl=en&ie=UTF-8 (7/29/2002).

Gray, D.M. and A.T. Leiser. 1989. *Biotechnical Slope Protection and Erosion Control*. Malabar, FL: Kreiger Publishing Co.

Griffin, D.W., C.A. Kellogg, and E.A. Shinn. 2001. Dust in the wind: Long range transport of dust in the atmosphere and its implications for global public and ecosystem health. *Global Change & Human Health* 2(1): 20–33.

Gupta, J.P. and P. Raina. 1996. Wind erosion and its control in hot arid areas of Rajasthan. In B. Buerkert, B.E. Allison, and M. Von Oppen (eds.), *Wind Erosion in West Africa: The Problem and Its Control*, pp. 209–218. Berlin: Margraf Verlag.

Haigh, M.J., J.S. Rawat, S.K. Bartarya, et al. 1995. Interactions between forest and landslide activity along new highways in the Kumaun Himalaya. *Forest Ecology and Management* 78(1–3): 173–189.

Hawkins, L. 2002. Ants. http://www.suite101.com/article.cfm/homeschooling_science_fun/69922 (12/17/2002).

Heywood, V.H. 1995. *Global Biodiversity Assessment*. Cambridge, UK: Cambridge University Press.

Huszar, P.C. and S.L. Piper. 1985. Off-site costs of wind erosion in New Mexico. In *Off-Site Costs of Soil Erosion: The Proceedings of a Symposium*, pp. 143–166. Washington, D.C.: The Conservation Foundation.

IECA. 1991. *Erosion Control—A Global Perspective*. Proceedings of Conference XXII. Steamboat Springs, CO: International Erosion Control Association.

IFPRI. 2002. Effective Strategies for Reducing Hunger, Poverty, and Environmental Degradation in Ethiopian Highlands. http://www.ifpri.cgiar.org/media/ifi_results.htm (10/8/2002).

Johnson, P.W. 1995. *Agriculture, Rural Development, Food and Drug Administration*. Washington, D.C.: Government Printing Office.

Jones, A.J., R. Lal, and D.R. Huggins. 1997. Soil erosion and productivity research: A regional approach. *American Journal of Alternative Agriculture* 12(4): 183–192.

Kendall, H.W. and D. Pimentel. 1994. Constraints on the expansion of the global food supply. *Ambio* 23, 198–205.

Kitazawa, Y. and T. Kitazawa. 1980. Influence of application of a fungicide, an insecticide, and compost upon soil biotic community. In D.L. Sindal (ed.), *Soil Biology as Related to Land Use Practices*, pp. 94–99. Washington, D.C.: Office of Pesticide and Toxic Substances, Environmental Protection Agency.

Klee, G.A. 1991. *Conservation of Natural Resources*. Englewood Cliffs, NJ: Prentice Hall.

Klocke, N.L., K.G. Hubbard, W.L. Kranz, et al. 1996. Evapotranspiration (ET) or crop water use. University of Nebraska Cooperative Extension. http://www.ianr.unl.edu/pubs/irrigation/g992.htm (10/8/2002).

Lal, R. 1990. Soil erosion and land degradation: The global risks. In R. Lal and B.A. Stewart (eds.), *Soil Degradation*, pp. 129–172. New York: Springer-Verlag.

Lal, R. 1994. Water management in various crop production systems related to soil tillage. *Soil & Tillage Research* 30: 169–185.

Lal, R. 2001. World cropland soils as a source of sink for atmospheric carbon. *Advances in Agronomy* 71: 145–191.

Lal, R. 2002. One answer for cleaner air, water: Better agricultural practices. http://www.acs.ohio-state.edu/units/research/archive/sequest.htm (12/17/2002).

Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. *Science* 304: 1623–1627.

Lal, R. and B.A. Stewart. 1990. *Soil Degradation*. New York: Springer-Verlag.

Lal, R., R.F. Follett, J. Kimble, et al. 1999. Managing U.S. cropland to sequester carbon in soil. *Journal of Soil and Water Conservation* 54(1): 374–381.

Langdale, G.W., L.T West, R.R. Bruce, et al. 1992. Restoration of eroded soil with conservation tillage. *Soil Technology* 5: 81–90.

Lavelle, P. 1983. The soil fauna of tropical savannas. II. The earthworms. *Ecosystems of the World* 13: 485–504.

Lazaroff, C. 2001. Biodiversity gives carbon sinks a boost. *Environment News Service* April 13.

Lee, K.E. 1985. *Earthworms: Their Ecology and Relationships with Soils and Land Use*. Orlando, FL: Academic Press.

Lee, E. and R.C. Foster. 1991. Soil fauna and soil structure. *Australian Journal of Soil Research* 29: 745–776.

Libert, B. 1995. *The Environmental Heritage of Soviet Agriculture*. Oxon, UK: CAB International.

Lockaby, B.G. and J.C. Adams. 1985. Pedoturbation of a forest soil by fire ants. *Soil Science Society of America Journal* 49: 220–223.

Martin, P. 1997. Sediments and erosion. http://www.gov.mb.ca/environ/pages/publs97/cwgtext/sediment.html (10/8/2002).

McLaughlin, L. 1991. Soil conservation planning in the People's Republic of China: An alternative approach. Dissertation, Cornell University, Ithaca, NY.

McLaughlin, L. 1993. A case study in Dingxi County, Gansu Province, China. In D. Pimentel (ed.), *World Soil Erosion and Conservation*, pp. 87–107. Cambridge, UK: Cambridge University Press.

McTainish, G. and C. Boughton. 1993. *Land Degradation Processes in Australia*. Melbourne: Longman Cheshire.

Mokma, D.L. and M.A. Sietz. 1992. Effects of soil erosion on corn yields on Marlette soils in South-Central Michigan. *Journal of Soil and Water Conservation* 47: 325–327.

Murphee, C.E. and K.C. McGregor. 1991. Runoff and sediment yield from a flatland watershed in soybeans. *Trans. ASAE* 34: 407–411.

Myers, N. 1993. *Gaia: An Atlas of Planet Management*. Garden City, NY: Anchor/Doubleday.

NAS. 2003. *Frontiers in Agricultural Research: Food, Health, Environment and Communities*. National Research Council, National Academy of Sciences. Washington, D.C.: National Academies Press.

Odum, E.P. 1978. *Fundamentals of Ecology*. New York: Saunders.

Olah-Zsupos, A. and B. Helmeczi. 1987. The effect of soil conditioners on soil microorganisms. In J. Szegi (ed.), *Soil Biology and Conservation of the Biosphere*, pp. 829–837. Proceedings of the 9th International Symposium. Budapest, Hungary: Akademiai Kiado.

Oldeman, L.R. 1997. Soil degradation: A threat to food security? Paper presented at the international conference on time ecology: time for soil culture–temporal perspectives on sustainable use of soil. 6–9 April 1997. Tutzing, Germany.

Olson, K.R. and E. Nizeyimana. 1988. Effects of soil erosion on corn yields of seven Illinois soils. *Journal of Production Agriculture* 1: 13–19.

Patric, J.H. 2002. Forest erosion rates. syllabus.syr.edu/esf/rdbriggs/for345/erosion.htm (12/17/2002).

Phillips, D.L., D. White, and B. Johnson. 1993. Implications of climate change scenarios for soil erosion potential in the USA. *Land Degradation and Rehabilitation* 4: 61–72.

Pimentel, D. 1993. *World Soil Erosion and Conservation*. Cambridge, UK: Cambridge University Press.

Pimentel, D. 1997. Soil erosion. *Environment* 39(10): 4–5.

Pimentel, D. 2001. The limitations of biomass energy. In *Encyclopedia of Physical Science and Technology*, 3rd edition, vol. 2, pp. 159–171. San Diego, CA: Academic Press.

Pimentel, D. and N. Kounang. 1998. Ecology of soil erosion in ecosystems. *Ecosystems* 1: 416–426.

Pimentel, D. and A. Warneke. 1989. Ecological effects of manure, sewage sludge, and other organic wastes on arthropod populations. *Agriculture Zoology Reviews* 3: 1–30.

Pimentel, D., U. Stachow, D.A. Takacs, et al. 1992. Conserving biological diversity in agricultural/forestry systems. *BioScience* 42: 354–362.

Pimentel, D., C. Harvey, P. Resosudarmo, et al. 1995. Environmental and economic costs of soil erosion and conservation benefits. *Science* 267: 1117–1123.

Pimentel, D., J. Houser, E. Preiss, et al. 1997. Water resources: Agriculture, the environment, and society. *BioScience* 47(2), 97–106.

PRB. 2002. *World Population Data Sheet*. Washington, D.C.: Population Reference Bureau.

Reid, W.S. 1985. Regional effects of soil erosion on crop productivity—northeast. In R.F. Follett and B.A. Stewart (eds.), *Soil Erosion and Crop Productivity*, pp. 235–250. Madison, WI: American Society of Agronomy.

Risser, J. 1981. A renewed threat of soil erosion: It's worse than the Dust Bowl. *Smithsonian* 11: 120–122, 124, 126–130.

Roose, E. 1988. Soil and water conservation lessons from steep-slope farming in French speaking countries of Africa. In *Conservation Farming on Steep Lands*, pp. 130–131. Ankeny, IA: Soil and Water Conservation Society.

Schertz, D.L., W.C. Moldenhauer, S.J. Livingston, et al. 1989. Effect of past soil erosion on crop productivity in Indiana. *Journal of Soil and Water Conservation* 44(6): 604–608.

SCS. 1993. Wind Erosion Report (Nov. 1992–May 1993). Washington, D.C.: Soil Conservation Service, USDA.

Shachak, M., C.G. Jones, and S. Brand. 1995. The role of animals in an arid ecosystem: Snails and isopods as controllers of soil formation, erosion and desalinization. In H.P. Blume and S.M. Berkowicz (eds.), *Arid Ecosystems*, pp. 37–50. Cremlingen-Destedt, Germany: Catena Verlag.

Singh, T.V. and J. Kaur. 1989. *Studies in Himalayan Ecology and Development Strategies*. New Delhi: Himalayan Books.

Solliday, L. 1997. Sediment transport of an estuary. http://bellnetweb.brc.tamus.edu/sediment.htm (1/10/2003).

Southgate, D. and M. Whitaker. 1992. Promoting resource degradation in Latin America: Tropical deforestation, soil erosion, and coastal ecosystem disturbance in Ecuador. *Economic Development and Cultural Change* 40(4): 787–807.

Speth, J.G. 1994. Towards an effective and operational International Convention on Desertification. United Nations, International Convention on Desertification, Int. Negotiating Comm., New York.

Stone, R.P. and N. Moore. 1997. Control of soil erosion. Factsheet. http://www.gov.pm.ca/OMAFRA/english/crops/facts/95-089.htm (12/18/2002).

Sugden, A.M. and G.F. Rands. 1990. The ecology of temperate and cereal fields. *Trends in Ecology and Evolution* 5: 205–206.

Sugden, A.M., R. Stone, and C. Ash. 2004. Ecology in the underworld. *Science* 304: 1613.

Sundquist, B. 2000. Topsoil loss—causes, effects, and implications: A global perspective. 4th edition. http://www.alltel.net/~bsundquist1/ (10/8/2002).

SWAG. 2002. Principles of erosion and sediment control. http://www.watershedrestoration.org/erosion.htm (8/10/2002).

Taddese, G. 2001. Land degradation: A challenge to Ethiopia. *Environment Management* 27(6): 815–824.

Tilman, D. and J.A. Downing. 1994. Biodiversity and stability in grasslands. *Nature* 367: 363–365.

Trimble, S.W. 1994. Erosional effects of cattle on stream banks in Tennessee, USA. Earth Surf. Process. *Landforms* 19: 451–464.

Trimble, S.W. and A.C. Mendel. 1995. The cow as a geomorphic agent—a critical review. *Geomorphology* 13: 233–253.

Troeh, F.R. and L.M. Thompson. 1993. *Soils and Soil Fertility*. 5th edition. New York: Oxford University Press.

Troeh, F.R, J.A Hobbs, and R.L. Donahue. 1991. *Soil and Water Conservation*. Englewood Cliffs, NJ: Prentice Hall.

UN-NADAF. 1996. UN-NADAF mid-term review: Focus on key sectors: Environment. *Africa Recovery* 10(2): p. 23. October 1996.

Uri, N.D. 2001. Agriculture and the environment—the problem of soil erosion. *Journal of Sustainable Agriculture* 16(4): 71–91.

USDA. 1989. The Second RCA Appraisal. Soil, water, and related resources on nonfederal land in the United States. Analysis of conditions and trends, Washington, D.C., U.S. Department of Agriculture.

USDA. 2000a. Changes in average annual soil erosion by water on cropland and CRP land, 1992–1997. Natural Resources Conservation Service. USDA. Revised December 2000.

USDA. 2000b. Changes in average annual soil erosion by wind on cropland and CRP land, 1992–1997. Natural Resources Conservation Service. USDA. Revised December 2000.

USDA. 2001. *Agricultural Statistics*. Washington, D.C.: US Department of Agriculture.

Walsh, K.N. and M.S. Rowe. 2001. Biodiversity increases Ecosystems' ability to absorb CO_2 and nitrogen. http://www.bnl.gov/bnlweb/pubaf/pr/2001bnlpr041101.htm (8/10/2002).

Wardle, D.A., R.D. Bardgett, J.N. Klironomos, et al. 2004. Ecological linkages between aboveground and belowground biota. *Science* 304: 1629–1633.

Watershed. 2002. Watershed conditions: Cumulative watershed effects. http://www.krisweb.com/watershd/impacts.htm (10/8/2002).

Weesies, G.A., S.J. Livingston, W.D. Hosteter, et al. 1994. Effect of soil erosion on crop yield in Indiana: Results of a 10 year study. *Journal of Soil and Water Conservation* 49(6): 597–600.

WEI. 2002. Wind Erosion Impacts. http://www.cahe.wsu.edu/~cp3/erosion/erosion.html (10/8/2002).

Wen, D. 1993. Soil erosion and conservation in China. In D. Pimentel (ed.), *Soil Erosion and Conservation*, pp. 63–86. New York: Cambridge University Press.

Wen, D. 1997. *Agriculture in China: Water and Energy Resources*. Shenyang, China: Institute of Applied Ecology, Chinese Academy of Science.

Wendt, R.C., Alberts, E.E., and Helmers, A.T. 1986. Variability of runoff and soil loss from fallow experimental plots. *SSSAJ* 50: 730–736.

WHO. 2004. World Health Report. http://www.who.int/whr/2004/annex/topic/en.annex_2_en.pdf (10/1/04).

Wind Particles. 2002. Wind particles and health. http://res2.agr.ca/research-recherche/science/Healthy_Air4d.html (4/29/2002).

Witt, B. 1997. Using soil fauna to improve soil health. http://www.hort.agri.umn.edu/h5015/97papers/witt.html (10/8/2002).

Wood, M. 1989. *Soil Biology*. New York: Blackie, Chapman & Hall.

World Problems. 1999. Encyclopedia of world problems and human potential. http://www/uia.org/uiademo/pro/d9118.htm (8/26/1999).

WRI. 1994. World Resources Institute. New York: Oxford University Press.

WRI. 1997. World Resources Institute. New York: Oxford University Press.

Wright, D.H. 1990. Human impacts on energy flow through natural ecosystems, and replications for species endangerment. *Ambio* 19: 189–194.

Young, A. 1989. *Agroforestry for Soil Conservation*. Wallingford, UK: C.A.B.

Young, A. 1990. Agroforestry, environment and sustainability. *Outlook on Agriculture* 19: 155–160.

Young, A. 1998. *Land Resources: Now and for the Future*. Cambridge, UK: Cambridge University Press.

Zacharias, T.P. and A.H. Grube. 1984. An economic evaluation of weed control methods used in combination with crop rotations: A stochastic dominance approach. *North Central Journal of Agricultural Economics* 6: 113–120.

Zhang, X., D.E. Walling, T.A. Quine, et al. 1997. Use of reservoir deposits and caesium-137 measurements to investigate the erosional response of a small drainage basin in the rolling loess plateau region of China. *Land Degradation and Development* 8: 1–16.

Ziemer, R.R. 1998. Flooding and stormflows. In R.R. Ziemer, technical coordinator, Proceedings of the Conference on Coastal Watersheds: The Caspar Creek Story. May 6, 1998; Ukia, CA. Technical Report PSW-GTR-168. Albany, CA: Pacific Southwest Research Station, USDA Forest Service, 15–24s.

16 Conservation of Biological Diversity in Agricultural, Forestry, and Marine Systems

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The present rate of species loss projects that half of all existing plant, animal, and microbe species on Earth will become extinct by the end of this century (Myers, 2003a; Wilson, 2003). This projected high rate of extinction due to human activities is alarming because many of these organisms are vital to the safe and productive function of ecological systems that sustain our planet and the global economy (Dirzo and Raven, 2003). Indeed, agricultural productivity and public health depend on the activities of diverse natural biota. From 10 to 50 million species of plants, animals, and microbes fulfill the ecological needs on Earth (Pimm et al., 1995; Pimm, 2002).

Although efforts to curb the loss of biodiversity have intensified in recent years, we have not been effective in countering the accelerating human population growth and the increasing destruction of natural habitats. The introduction of alien invasive species throughout the world continues to alter and damage natural and managed ecosystems (Pimentel, 2002). Moreover, additional complementary strategies are needed to protect small organism species, such as insects, bacteria, and fungi, which are essential to the structure and function of natural ecosystems (Wilson, 1987; Price, 1988; Soil Organisms, 2004).

Establishing national parks has been the prime focus of world biological conservation. Often overlooked but equally vital is the protection of biological diversity existing in our vast agricultural and forest ecosystems, as well as within human settlements (Pimentel et al., 1992; Daily et al., 2001; Ricketts, 2001; Vandermeer, et al., 2002; Homer-Devine et al., 2003). Together these cover approximately 78% of productive terrestrial ecosystems (AAAS, 2001).

In this chapter, we examine the necessity of species diversity in maintaining healthy and productive ecosystems as well as specific threats to biodiversity. The goal is to identify ecological strategies and policies that help enhance the conservation of biological diversity in natural, agricultural, forest, marine, and natural ecosystems.

CAUSES OF REDUCED SPECIES DIVERSITY

Over the past billion years, the natural processes of adaptation and diversification have tended to increase the number of species. However, especially over the past several centuries, the rapid escalation of human numbers (PRB, 2003) and the movement of humans into wild areas have resulted in a major and continuous decline in species diversity (Wilson, 1988; Novacek, 2001).

The rapid disappearance of animal and plant species is clearly illustrated in Britain. Thomas et al. (2004) report that butterfly species have declined 71% during ~20-year period, bird species declined 54% over 20 years, and native plants species showed a 28% decline over 40 years.

In developed countries, the use of natural resources is 100–600 times more per capita than in developing countries (Conservation Issues, 2003; Pimentel and Pimentel, 2003). Even where progressive laws and land preservation efforts exist, the increasing demands of humans and their industries undermine biodiversity preservation and the value of various ecosystems (Machlis and Tichnell, 1985; Pimentel and Pimentel, 2003).

When the demand for resources necessary for sustaining the increasing human population exceeds what is available, the result is increasing malnutrition and stress. More than 3 billion people are currently malnourished worldwide—facing shortages of calories, protein, vitamins A, B, D, and E, iron, and iodine (WHO, 2000). This is the largest number of malnourished people in history.

DEFORESTATION AND DESTRUCTION OF NATURAL HABITATS

Tropical forests occupy only 6.5% of the world's terrestrial ecosystems, but are home to about 70% of the world's species (N. Myers, personal communication, Oxford University, 2004; Pimm, 1991, 2002; Pimm and Brown, 2004). To date, humans have destroyed more than half of the world's tropical forests. For example, two-thirds of the forest area in Central America has been converted to agriculture for livestock production (Robbins, 2001; Rainforest, 2003). About 19 million ha of forests (about the size of Florida) are destroyed each year worldwide (World Bank, 2002), and approximately 60% of this deforestation is due to the conversion of forests to agricultural lands to maintain fiber and food production (Earthscan, 2002; Deforestation, 2003).

The destruction of even one tree species can have cascading effects resulting in significant losses of species, because up to 1000 arthropod species, including parasites and predators, may be associated with that single tree species (Erwin, 1983). Also, approximately 30 associated animal and microbe species die out for every plant species that becomes extinct (Edwards, 1998).

Equally disturbing to the loss of plant species is the rapid loss of crop genotypes now occurring. Crop genotype diversity is vital to farmers in different climatic and regional conditions, as they encounter different complexes of pest insects, weeds, and plant pathogens (James, 1999).

SOIL EROSION AND SALINIZATION

Each year an estimated 10 million ha of cropland worldwide are abandoned due to lack of productivity caused by soil erosion (Faeth and Crosson, 1994). Another 10 million ha/year are critically damaged due to salinization, in large part as a result of irrigation or improper drainage methods (Thomas and Middleton, 1993).

Erosion rates on cropland in Asia, Africa, and South America average 30–40 t/ha/year (Taddese, 2001). In some regions, like Ethiopia, erosion rates on cropland may average as high as 100 t/ha/year (Taddese, 2001). While the current rate of soil erosion from cropland in the United States is less than in many developing countries, it is still about 10 t/ha/year, which is 10 times faster than the soil formation rate (NAS, 2003; Uri, 2001). The economic cost of erosion in the United States is estimated at about $38 billion per year (Uri, 2001), while for the rest of the world economic losses are estimated to be $400 billion per year (Myers, 2003b).

The first component of the soil loss, due to erosion by rainfall and wind, is soil organic matter. This loss directly reduces the biomass of soil, vital to the survival of plants, animals, and microbes. In addition, the reduction of soil depth can hinder or totally destroy the land's productivity (Uri, 2001).

In streams and lakes, the eroded sediment clouds water, reduces sunlight, and kills fish and other biota (Ontario, 1987; Uri, 2001). Also, the addition of nitrogen, phosphorus, and other nutrients to waterways may increase "undesirable" algae and other aquatic weeds and cause oxygen shortages (hypoxia), making the water inhospitable to fish and other animal species (USDA, 1999). For example, approximately 40% of U.S. fresh water is deemed unfit for recreational or drinking water uses because of erosion-induced contamination with dangerous microbes, pesticides, and fertilizers (UNESCO, 2001).

Finally, a growing number of acres are sacrificed to urban and economic development. Presently, nearly 16 million ha of U.S. land are devoted to roads and parking lots (Brown, 2001). Each person requires 0.4 ha of land for urbanization and highways (Anok and Peace, 2003), plus 0.5 ha of cropland, and 1.8 ha for pasture and forests (USDA, 2002). As the human population expands, so do the number of hectares required for economic development.

ALIEN BIOLOGICAL INVADERS

Rapid human population growth and loss of natural habitats are reducing species numbers, but equally important are biodiversity losses due to the invasions of alien biological species (Pimentel et al., 2000; Sala et al., 2000; Pimentel, 2002). To date, more than 50,000 alien invasive species have been introduced into United States, and some are causing more than $120 billion in damages and control costs each year (Pimentel et al., 2005a). Harmful competition, predation, and parasitism from invasive species are causing an estimated 40% of all native species extinctions in the United States and forcing other native species to become endangered or threatened (Pimentel, 2002).

Human activities are facilitating the introduction of alien species and removing native vegetation in natural ecosystems for crops, livestock, and urbanization, and thereby contributing to the decline in species diversity (Tuxill, 1999; Henry, 2001; Pimentel, 2002).

CHEMICAL POLLUTANTS

Globally, one of the major factors causing species loss is the growing presence of chemicals throughout the world (Environmental Threats, 2003; Do or Die, 2003). Humans worldwide use 100,000 chemicals. More than 500,000 kg of synthetic pesticide chemicals are applied annually for U.S. agriculture, public health, and other purposes (Pimentel, 1997). Even the recommended use of pesticides destroys many beneficial species each year. Pesticide use in U.S. agriculture, for instance, kills more than 72 million adult birds each year, damages a half million colonies of honey bees, and is equally hazardous to wild bees (Pimentel, 2005). Additionally, some pesticides wash into streams and lakes, destroying fish and other aquatic organisms (Pimentel, 2005). In addition to animals, there are 300,000 human poisonings with 45 deaths in the United States and 26 million human poisonings worldwide with 220,000 deaths (Pimentel, 2005).

MARINE ECOSYSTEMS AND AQUACULTURE

Although studies most often focus on loss of terrestrial biodiversity, the oceans and other aquatic ecosystems are also suffering tremendous species losses. The Food and Agricultural Organization (FAO, 2003b) estimates that 47% of the world's fishery stocks are fully exploited and 28% are overexploited. Today, the estimated biomass of large predatory fish is only 10% of preindustrial levels (Myers and Worm, 2003), and marine foodwebs have significantly changed (Pauly et al., 1998). Although pollution, climate change, and invasive species threaten marine ecosystems, the fishing industry exerts the greatest pressure, even though fish make up a relatively small part of the world's human diet (0.01% of calories or 16% of animal protein (FAO, 2002a)). In seeking target fish for harvest, many nontarget fish are caught and destroyed. For every kilogram of shrimp harvested, 8–9 kg of "trash" fish are mangled and discarded as bycatch (Earle, 1995).

Some suggest that aquaculture will replace ocean fishing. Already, aquaculture is supplying nearly 30% of the world's fishery products (FAO, 2003b). However, overlooked is the fact that the production of aquaculture fish requires the harvesting of ocean fish. For instance, each kilogram of farm-fed salmon requires from 3 to 5 kg of ocean fishmeal (Goldberg et al., 2001). In this way, aquaculture is putting additional pressure on ocean fisheries rather than reducing pressure.

About two-thirds of fish species have an early stage of development in coastal wetlands (Ramsar, 2000). Thus, when coastal wetlands are drained or destroyed, fish production is seriously affected.

There are also economic consequences of reduced marine biodiversity. For example, if a fishery collapses, thousands of fishermen may lose their jobs. This happened in 1992 when 40,000 fishermen on the eastern coast of Canada lost their jobs because of the collapse of cod fishery due to overfishing (Harder, 2003).

GLOBAL CLIMATE CHANGE

Many birds and insects have already extended their distributions northward or to higher altitudes, mainly attributed to global warming. In response to climate change, many species in the 25 biodiversity hotspots will be forced to extinction (Myers, 2003b). In the coming decades, projected global climate change could seriously damage the world's species (Hansen et al., 1996; WRI, 2002). Moreover, many species, like trees, may not be able to change their distributions rapidly enough to keep up with the changing climate (Krajick, 2001, 2004; WRI, 2002). The World Conservation Union projects global warming may threaten 37% of the world's species by 2050 (Thomas et al., 2004).

Marine ecosystems are also at great risk due to climate change. For instance, even mild increases in ocean temperatures cause major epidemics of coral bleaching. Such increases in 1998 resulted in a loss of one-sixth of the world's coral colonies (Goreau et al., 2000; Earthscan, 2002; Dennis, 2002).

BIOLOGICAL DIVERSITY

Although about 90% of the global food supply today comes from 15 plant and 8 animal species (Pimentel and Pimentel, 1996), throughout history people have used as many as 20,000 plant species for food, out of the more than 80,000 species that could be utilized (Vietmyer, 1995; Tuxill, 1999). Humans obtain 99% of their food and all of their wood products by harvesting them from 70% of terrestrial temperate and tropical ecosystems (Pimentel et al., 1999; AAAS, 2001). Of the Earth's terrestrial area, approximately 11% is devoted to cropland, 37% to pasture land, 30% to forests, and about 5% to urbanization and highways (UNESCO, 2002; AAAS, 2001; Wiebe, 1997). The remaining 17% consists of unproductive areas, including mountains and deserts. Overall, most species are located on land area that is maintained for agriculture, forestry, and human settlements (Western and Pearl, 1989; Pimentel et al., 1992; FAO, 2004). Therefore, major efforts should be made to conserve the many species that now exist in these extensive managed, terrestrial environments (Paoletti, 1999a).

Current data suggest that 10–50 million species exist on Earth (Pimm et al., 1995). Most of what is known about biodiversity pertains to large plants and animals, such as flowering plants and vertebrates. The extent of the diversity of small organisms like bacteria, fungi, insects, mites, and other minute organisms remains relatively obscure. The United States is home to an estimated 750,000 species, of which small organisms, such as arthropods and microbes, comprise 95% (Pimentel et al., 1992; Dorworth, 2002).

In temperate crop ecosystems, the numbers of arthropod species range from 600 to 1000 species per hectare, while an estimated 20,000 bacteria species may be present in a favorable soil habitat (Table 16.1). Worldwide, arthropods make up

TABLE 16.1
Plant, Animal, and Microbe Species and Biomass Potential in a Favorable Soil Ecosystem with Ample Soil Organic Matter and Moisture

No. Species/ha		Sources	kg/ha	Sources
Bacteria	20,000	a,b	3.000	a
Fungi	50	a	3.000	c
Algae	5	d	100	c,e
Protozoa	60	a	100	c
Nematodes	30	a	50	c
Earthworms	15	a	3.000	a,f
Mites	114	g	10	a
Collembola	70	a	3	c
Enchytraeids	22	a	70	a
Termites	60	a	30	a
Ants	40	a	100	a
Isopoda	4	a	1	h
Beetles	46	i	70	a
Diptera	10	a	400	a
Arachnida	62	i	400	a
Total				

[a] Lavelle and Spain (2001).
[b] Wayne et al. (1987).
[c] Metting (1993).
[d] Masyuk (2002).
[e] Alexander (1977).
[f] Edwards and Bohlen (1996).
[g] Osler and Beattie (2001).
[h] Thimmayya (1998).
[i] Rushton et al. (1989).

the majority (~90%) of multicellular species. To illustrate, in a tropical forest in Uganda, on 80 trees of just two tree species, a total of 1352 beetle species were identified. In Borneo on 10 trees, a total of 2800 arthropod species were reported (Table 16.2). Arthropods and microbes, such as bacteria and fungi, contribute large amounts of biomass and large numbers of species to soil, crop, and forest ecosystems (Tables 16.1 through 16.3).

Marine ecosystems also have an abundance of species. For instance, 1 L of seawater may contain from 100 to 1000 species of bacteria (Fred Dobbs, Old Dominion University, personal communication, 2004). On coral reefs, for example, it is estimated that only 10% of the species have been described; over one million species are thought to inhabit these ecosystems making reefs rivals of rainforests in terms of diversity (Thorne-Miller, 1999).

TABLE 16.2
Arthropod Biodiversity in Various Ecosystems

Ecosystem	Location	Arthropod Species	Source
Alfalfa (per ha)	New York	600	a
Corn (monoculture)	Minnesota	600	b
Cotton (monoculture)	Arkansas	600	c
Pasture (per ha)	Britain	1.000	d
Two tree species (80 trees)	Uganda (beetles)	1352	e
Forest tropical (10 trees)	Borneo	2800	f

[a] Pimentel and Wheeler (1973).
[b] Warters (1969).
[c] Whitcomb and Godfrey (1991).
[d] MacFadyen (1961).
[e] Wagner (2003).
[f] Stock (1988).

TABLE 16.3
Biomass of Various Organisms per Hectare in a Temperate-Region Pasture

Organism	Biomass (kg fresh weight)
Plants	20,000[a]
Fungi	4000[b]
Bacteria	3000[b]
Arthropods	1000[a]
Annelids	1320[b]
Protozoa	380[b]
Algae	100[c]
Nematodes	50[c]
Mammals	1.2[d]
Birds	0.3[d]

[a] Estimated.
[b] Richards (1974).
[c] Metting (1993); Alexander (1977).
[d] Walter (1985); Xerces Society (2001).

PRESERVATION OF BIOLOGICAL DIVERSITY—LARGE AND SMALL ORGANISMS

Clearly, plants, fish, birds, and mammals are invaluable contributors to the health of the ecosystem (Krajick, 2001). An estimated 275,000 species of plants have been identified, and perhaps as many as 100,000 more plant species have yet to be discovered (IUCN, 2002a). Despite their general resilience, the survival of many plants is now in peril: for every ten species of plants and animals that are listed as endangered, approximately six of these species are plants (IUCN, 2002a). According to Walter and Gillett (1998), at least one of every eight known plant species is threatened with extinction.

The fate of larger organisms too remains a concern: one in every four mammals and one in every eight birds are facing a high risk of extinction in the near future (IUCN, 2004). However, the importance of small organisms that dominate the basic structure and function of ecosystems cannot be overstated (Terborgh, 1988; USGS, 2003). Small organisms, such as insects, are useful indicators for the overall "health" of an ecosystem and its capacity to provide vital services to humans (Paoletti, 1999b; ESA, 2003). Insects and other "little things," like bacteria and fungi, perform crucial functions that sustain ecosystems in ways that are still scarcely understood, including pollinating plants and degrading wastes (Wilson, 1987; Price, 1988; FAO, 2003a). Because small organisms may be more specialized and more closely associated with a plant species than larger animals, they are likely to be more susceptible to environmental changes (Dourojeanni, 1990; IUCN, 2002b). For example, it is estimated that for each tropical plant species facing extinction, approximately 20 species of arthropods feeding on a particular plant may also be forced to extinction (Erwin, 1983).

In general, ecosystems require a sound relationship among the various species that make up the system. The elimination or addition of even one species to a relatively balanced ecosystem can have profound, cascading, and largely unpredictable effects (Fritts and Rodda, 1998).

BIODIVERSITY AND ECONOMIC AND ENVIRONMENTAL BENEFITS

U.S. agriculture and forestry depend upon most of the estimated 750,000 species of natural plant, animal, and microbe species for production and sustainability (Pimentel et al., 1997). Plant, animal, and microbe species provide the basic food, fiber, and shelter to support U.S. agriculture and forestry and contribute more than $15 trillion dollars annually to the U.S. economy (USBC, 2002).

A most vital activity carried out primarily by invertebrates and microbes is recycling wastes produced by agriculture, forestry, and human activities. A conservative estimate of the annual benefits of these processes in the United States alone is $62 billion annually (Pimentel et al., 1997).

Moreover, approximately two-thirds of the world's flowering plants depend on insect and other pollinators for reproduction and survival (Native Pollinator, 2003). Specific pollinators are sometimes vital to a particular species of plant (LaSalle and Gould, 1993; Comba and Corbet, 1998). This cross-pollination by bees is essential to about one-third of the crops grown in the United States and has a value of about $40 billion per year (USBC, 2002). Some seed-eating birds and mammals, like rodents, are essential in the dispersal of some plant seeds as well (Reid and Miller, 1989).

An estimated $10 billion is spent annually in the United States for pesticides to control crop pests. But the parasites and predators that exist in natural ecosystems provide an estimated $40 billion per year in benefits for pest control. Without the existence of natural enemies, crop losses by pests in agriculture would increase 10%–20%. Then the amount of pesticides and costs of chemical pest control would escalate (Pimentel et al., 1997).

Fish, other wildlife, and plant materials harvested from the wild in the United States alone have an estimated annual value of $45 billion (USBC, 2002). For instance, the livelihood of more than 30 million fishers and fish farmers worldwide (most of which live in developing countries) comes from fisheries (FAO, 2002b). The United States alone has a $25 billion fishing industry (USBC, 2002). In addition, approximately 25% of all pharmaceuticals manufactured in the United States, valued at $20 billion, are obtained directly or indirectly from plant materials (Tuxill, 1999).

Sustainable and productive agriculture and forestry systems cannot function successfully without the vital activities contributed by a wide diversity of natural plants, animals, and microbes.

PLANT, ANIMAL, AND MICROBE BIOMASS AND DIVERSITY

Biological diversity in an ecosystem is related to the amount of living and nonliving organic matter present (Elton, 1927; Wright, 1983; Sugden and Rands, 1990; Mishra and Dhar, 2004).

In addition to plants, the data in Table 16.3 indicate that fungi, bacteria, annelids, and arthropods contribute the bulk of the nonplant biomass in a pasture ecosystem. The fungi alone comprise about 4000 kg/ha (wet), bacteria about 3000 kg/ha (wet), earthworms 1300 kg/ha (wet), and arthropods 1000 kg/ha (wet). In contrast, mammals and birds contribute only 1.2 and 0.3 kg/ha (wet) biomass, respectively. Because the abundance of biomass is most often positively correlated with biodiversity, efforts to increase biomass in agricultural and forestry ecosystems are an important factor in the preservation of the wealth in biodiversity (Elton, 1927; Wright, 1983; Sugden and Rands, 1990; Mishra and Dhar, 2004).

STRATEGIES FOR CONSERVING BIOLOGICAL DIVERSITY

Because agriculture, forestry, and human settlements occupy about 78% of the terrestrial environment, a large portion of the world's biological diversity coexists with humans in these ecosystems (Western, 1994). Therefore, major efforts should be made to conserve the many species that now exist in these extensive, managed, terrestrial environments. Conservation programs based on sound ecological principles will assist agriculture and forestry production in becoming more sustainable, while at the same time maintaining biological diversity (Heywood, 1999; NAS 2003).

Species diversity benefits from abundant biomass, habitat diversity, stable ecosystems, abundant soil nutrients, high-quality soils, effective biogeochemical cycling, abundant water, and healthy marine systems (Westman, 1990).

Abundant Biomass—Except for green plants that capture solar energy for themselves and certain bacteria that use inorganic material as an energy source, all other organisms rely on plant biomass as their primary or secondary energy source. Crop and forest residues are biomass resources that are vital to agricultural and forest production. They not only protect the soil from erosion and conserve water, but, when recycled, also contribute large quantities (2000–15,000 kg/ha [dry]) of nutrients and organic matter to the soil (ERAB, 1981; NAS, 2003). Suggestions that crop residues be harvested for fuel and other purposes have proven catastrophic (Fenster, 2003; Pimentel and Wen, 2004). In China and India, the removal of crop residues has increased the rates of soil erosion and rapid water runoff approximately 10-fold and reduced soil quality and fertility (Fenster, 2003; Pimentel and Wen, 2004). In addition to reducing soil erosion and water runoff, cover crops are also advantageous for agricultural production because they reduce soil erosion, compaction, suppress weeds, conserve soil nutrients and moisture, and increase soil organic matter (Pimentel et al., 2005b). Furthermore, cover crops can increase vegetative biomass and diversity in crop ecosystems because they provide additional shelter and refuges for many species.

PLANT SPECIES DIVERSITY

Approximately half of the plant species in the United States exist in managed ecosystems. Of the estimated 17,000 plant species in the United States (Morin, 1995), approximately 6000 are crop species and 2000 are weed species (Pimentel et al., 2000).

Increased plant diversity, with associated species diversity, can be encouraged in some managed ecosystems. Multispecies crop systems support a diverse group of natural biota that increase productivity. At the same time, farmers benefit from the effective use of soil nutrients and reduced water runoff. Examples of such cropping systems are found in Java, where small farmers cultivate more than 600 crop species in their gardens, making for overall species diversity comparable to subtropical forests (Dover and Talbot, 1987). In Guatemala, about 279 species were reported in the tropical-humid gardens (IPGRI, 2004). Similarly, nearly 80% of the farmers in West Africa and Latin America intercrop their gardens, raising upwards of 100 different crop species on their small plantings (Thrupp, 1998). By increasing the number of plant species on their farms, farmers were able to increase food production with a high degree of diversity.

INTERCROPPING

When leguminous crops, such as clover, are grown between crop rows, such as corn, they serve as an intercrop or living mulch. Not only do legumes fix nitrogen in the soil, but they also conserve soil and water resources, and at the same time increase the associated biomass and animal and plant diversity present in the ecosystem (Sigvald and Yuen, 2001).

Strips of different crops are especially helpful when planted across the slope of agricultural fields. Such strips not only help control soil erosion and water runoff, but also increase the diversity of vegetation and thus increase the availability of beneficial parasites and predators for biological control (Francis et al., 1986; Fortin et al., 1994; Ramert, 2002). With appropriate combinations of strip crops grown *in rotation*, various pests can be controlled with little or no pesticides. Such pest control occurs, for example, when corn, soybeans, and wheat are grown in rotation in strip patterns (Pimentel et al., 1993, 2005b).

Shelter Belts and Hedgerows

Shelter belts and hedgerows planted along the edges of cropland and pasture land also contribute to biological diversity because, like intercrops, they reduce soil erosion and moisture loss as well as increase the biomass and structural and habitat diversity present in managed ecosystems (Elton, 1927; NAS, 1988; HMSO, 1995). Organic hedgerows are superior to hedgerows associated with conventional agriculture. For example, in Denmark, organic hedgerows were comprised of 27% more plant species than conventional hedgerows (Aude et al., 2003). Furthermore, shelter belts and hedgerows frequently provide refuges for beneficial parasites and predators, like ground beetles, that help control pest insects and weeds, thereby reducing the need for pesticides (Paoletti et al., 1989; Whalon, 2002). In addition, shelter belts help reduce erosion and moisture loss from crops by buffering winds and are especially beneficial in areas with low rainfall and high winds (Kedziora et al., 1989; Lu and Lu, 2003).

Biomass and Soil and Water Conservation—High quality soils maximize plant biomass productivity and help increase biodiversity. In general, quality soils are rich in nutrients; high organic matter (5%–10% of soil by weight); store soil moisture (about 20% by weight); are well drained and relatively deep (>15 cm); and have abundant soil biota (Doran and Parkin, 1994).

Abundant vegetative cover, including nonliving plant residues, prevent soil erosion and rapid water runoff (Hayes, 1996). Organic matter not only harbors large numbers of species but, equally important, sustains the productivity of the soil by improving water-holding capacity, providing a source of nutrients, improving soil tilth, and increasing the number and diversity of soil biota (Table 16.1). Because soil organic matter is the first to suffer the effects of erosion, soil conservation is vital to maximize biomass productivity and biodiversity.

A strong association exists between precipitation, plant diversity, and productivity. Because all plants and animals require water to sustain themselves, sufficient water is vital for maintaining maximum productivity and biodiversity (Neveln, 2003). Plants require large amounts of water for photosynthesis. For example, a corn crop producing 18,000 kg/ha of biomass during the growing season requires about 9 million L of water per hectare (Pimentel et al., 2004a).

Many technologies can be employed to conserve water and soil resources (crop rotations, strip cropping, contour planting, terracing, ridge planting, no-till, grass strips, vegetative cover, drip irrigation, intercropping, and shelter belts) (Troeh et al., 1999).

The adaptability of each technique depends on the particular characteristics of the crop or forest ecosystem (Troeh et al., 1999). In general, the presence of abundant biomass also conserves water by slowing rapid water runoff and increases the water holding capacity of the soil.

LIVESTOCK MANURE

Livestock manure, when properly used, is a valuable resource that increases the biomass and biodiversity in agricultural systems. For example, when manure (100 t/ha wet) was added to agricultural land in Hungary, the biomass of soil microbes increased 10-fold (Olah-Zsupos and Helmeczi, 1987).

HABITAT DIVERSITY

Increasing the diversity of physical habitats increases the diversity of associated plants and other organisms present in the ecosystem (Allee et al., 1949; Fletcher, 1995). For example, when the habitat area was increased 10-fold, the number of bird species increased 1.6- to 2.5-fold (Avian Ecology, 2003).

Arnold (1983) reported that only 5 bird species were present in a pure farming ecosystem surrounded solely by farmland. The bird species increased to 12 when there was a short hedge, 17 species when there was a tall hedge, and 19 species when a strip of woodland was present.

Corridors between habitats are essential for many large predators, such as coyotes and mountain lions, which actively move between suitable habitats (Rodriguez et al., 2003).

AGROFORESTRY

Agroforestry is an ecologically based, natural resource management system that integrates trees into cropland and rangeland systems (Leakey, 1997). Agroforestry increases biomass and conserves soils and water resources by preventing erosion (Kidd and Pimentel, 1992). Further, crop losses due to pests are often reduced because of increased plant diversity (Schroth et al., 2000). In addition to all these benefits of agroforestry, biological diversity is conserved and in some cases enhanced (CGIAR, 2003; Griffith, 2000).

For example, in tropical Central America, conventional corn plantings produce approximately 2000 kg/ha of dry biomass, whereas in an agroforestry system with a leguminous tree, the corn biomass was approximately doubled to about 3800 kg/ha (Kidd and Pimentel, 1992). At the same time, 4500 kg/ha of leguminous tree biomass was produced. Thus, in the agroforestry system, the total biomass produced was increased more than four times over that of the conventional system.

Similarly, in Indonesia, for example, agroforestry increased plant diversity above that in conventional farming with some farmer gardens having 50%–80% of the plant diversity found in natural forests (Leakey, 1997; Nobel and Dirzo, 1997). When the forests in the Tamaulipas region of Mexico were managed as agroforestry systems, they contained more than 300 plant species (Perfecto et al., 1996).

MIXED FORESTS

Mixed forests produce approximately 20% more biomass than a homogenous stand of trees (Ewel, 1986; Moore, 2002). The benefits are attributed to the differing nutritional need of the trees in the forest. In addition, mixed forests improve biological diversity because of the multiple arthropods and microbes associated with each tree species.

Moreover, in commercial forestry, as well as in natural forests, tree diversity increases biomass production by diminishing pest attack on tree hosts (Ewel, 1986; Allen, 2003). For example, the attack of the white-pine weevil on white pines and the Douglas-fir tussock moth on Douglas fir are significantly more severe in areas with single species forest than in areas with high tree species diversity (Allen, 2003).

Careful selective cutting of forests, however, can maintain high biological diversity and a healthy productive forest ecosystem (Hansen et al., 1996). Large-scale clear-cutting of forests should be avoided because it not only reduces biomass and biological diversity, but also removes nutrients from the soil, which eventually reduces the productivity of the entire ecosystem. Both biomass production and biological diversity decline as a result. Planting trees along streams is another helpful strategy to increase biodiversity as well as reduce erosion and conserve nutrients (Streams for the Future, 2004).

In addition, important agroecosystems are also found below ground in mature forests. When forests are cleared, vital mycorrhizal fungi and other micro-flora and fauna are reduced or exterminated (Tallis, 2002).

PASTURE MANAGEMENT

A pasture management strategy that maintains maximum biomass, while preventing overgrazing, is the most productive strategy for livestock and ecosystem biodiversity (Clark et al., 1986; McIntyre, 2001). In addition to providing livestock with forage and vegetative cover, pasture productivity prevents soil erosion and rapid water runoff. Parol (1986, 2003) reports that increasing the plant species diversity in pastures can increase the productivity of the pastures up to 10%.

To prevent overgrazing, the pasture should have the appropriate number of animal units per hectare and should employ a sound pasture rotation system (Beetz, 2001; Rotational Grazing, 2004). For example, in the northeastern region of the United States, maximum production of livestock was achieved when pastures were grazed for several weeks and then rested for several weeks to allow vegetative growth (Yohn and Rayburn, 2004).

PESTICIDE REDUCTION

Pesticides severely reduce biological diversity by destroying a wide array of both harmful and beneficial species in agricultural ecosystems. In this process, they change the normal structure and function of the ecosystem. Concern for the negative effects of pesticides on natural biota and public health has prompted some nations to reduce pesticide use. For example, Sweden has reduced pesticide use by 68% and

Indonesia by 65% without reducing crop yields. In the case of Indonesia, crop yields actually increased 12% (PCC, 2002; Oka, 1991).

By employing appropriate biological controls and other environmental practices in agriculture, pesticide use can be reduced, and in some cases eliminated, while maintaining or increasing crop yields (Pimentel et al., 1993; NAS, 2000).

CONSERVING FISHERIES

While many national and international fishery agreements do exist, they have not been enforced, as evidenced by the declining fish catches in recent years. Pauly and Watson (2003) recommend stricter regulations, including banning certain types of fishing gear. Furthermore, aquaculture that currently produces carnivorous fish, such as salmon, requires large quantities of fish meal (Goldberg et al., 2001). Alternatively, to be sustainable, aquaculture might have to rely increasingly upon herbivorous fish, such as catfish and tilapia (Gomiero et al., 1999; Swing, 2003).

PROTECTED PARKS

The maintenance of protected parks and wildlife refuges occupy about 12% of the terrestrial ecosystem (Chape et al., 2003). However, these parks are not protected from outside assault. For instance, about one-third of the tropical parks are already subject to encroachment by landless individuals who live in poverty (Myers, 2002). Many of these poor people who have an income of less than $1 per day are forced to attempt to find food or produce food in parks. As for protecting and effectively managing national parks, wildlife refuges, and other protected areas, it is reported that less than one quarter of the declared areas in 10 key forested countries were well managed, many had no satisfactory management at all (Heywood, A.H., personal communication, University of Reading, UK). Further support of this concern comes from the World Wildlife Fund study entitled, "How Effective are Protected Areas?" (World Wildlife Fund, 1999).

The further concern is that most parks are too small to insure the conservation of the majority of species they contain. For instance, the succulent Karoo biome in South Africa covers a relatively small area; however, this biome holds more than 6000 plant species, of which 40% are endemics, in addition to many endemic animals (Rodriguez et al., 2003). In Mexico on the El Eden Ecological reserve, only 73 species of slime molds are present, compared with 244 species in all of Mexico (Gomez-Pompa, 2004). Similarly, in Kenya, about 7% of its land is in protected national parks; however, 75% of the wildlife lives outside parks and within human systems (Western and Pearl, 1989; Muriuki, 2003). Including arthropods and microbes, more than 90% of species live outside of protected parks (Rodriguez et al., 2003).

Marine reserves, which comprise less than 1% of all marine ecosystems (WRI, 2002), have been widely promoted as conservation and fishery management tools. The benefits of marine reserves are indisputable, for within and around marine parks, fish populations increase dramatically and adjacent fisheries are improved up to 90% (Roberts et al., 2001). In addition, marine protected areas can provide substantial tourism revenues. For example, Australia's Great Barrier Reef Marine

Park yields over $1 billion per year in revenue for the local economy while costing a mere $20 million to manage (Hinrichsen, 1998).

GLOBAL CLIMATE CHANGE

With only 4% of the world's population, the United States is responsible for more release of carbon dioxide than any other nation in the world (about 25% of the total releases) (PRB, 2003). Reducing the rate of release of carbon dioxide and other greenhouse gases and slowing global warming will require a major effort by Americans and other people of the world. Hopefully, the United States will become the leader instead of an opponent of international climate policy. The United States could save as much as $430 billion per year on energy costs while reducing carbon dioxide emissions 30% below 2004 levels in 10 years (Pimentel et al., 2004b).

CONCLUSION

The present rate of species loss suggests that half of all species on Earth may be lost at the end of the twenty-first century. Millions of species of plants, animals, and microbes carry out vital functions in the biosphere, especially for agriculture, forestry, and aquatic systems. The prime threats to biodiversity result from rapid human population growth, and include habitat loss, urbanization, chemical use, introduced alien species, pollution, and global warming.

Conservationists are dedicated to protecting biodiversity and implementing sound conservation policies. Unfortunately, most conservation policies are established by economic planners, agriculturists, foresters, and corporations, and do not come from conservationists themselves (Myers, 2002). In the light of species loss and growing pressures on biodiversity worldwide, it appears that the only way that biodiversity can be saved is by saving the total biosphere (Myers, 2002).

One win-win approach is to strive for sustainable agriculture and forestry systems because most plant, animal, and microbe species exist in these ecosystems that cover 78% of the terrestrial ecosystem (Pimentel et al., 1992; Daily et al., 2001; Ricketts, 2001; Vandermeer et al., 2002; Homer-Devine et al., 2003). Also, agriculture and forestry ecosystems are the most favorable systems in terms of moisture, soil, nutrients, and temperatures. Maintaining biological diversity is essential for sustainable and productive agriculture and forestry systems. Biological diversity can best be protected by maintaining abundant biomass and habitat diversity; conserving soil, water, and nutrient resources; reducing water, soil, and air pollution; and reducing global warming.

The public as well as political leaders, must give high priority to protecting biodiversity and the total biosphere. We recommend that the United States and other nations adhere to the following policies to enhance the conservation of biodiversity:

- Encourage and implement ecologically sound and sustainable management practices for agriculture, forestry, and fishery systems.
- Implement policies to prevent the introduction of alien invasive species in the United States and other nations.
- Implement various international agreements, including the Convention on Biological Diversity, Framework Convention on Climate change,

and the Convention on the Law of the sea (J.A. McNeely, personal communication, Chief Scientist, IUCN, The World Conservation Union, Gland, Switzerland, 2004).

- Reduce water, air, and soil pollution that threaten species survival.
- Conserve and reduce fossil energy consumption to reduce greenhouse gases and global climate change.
- Set aside more ocean as enforced marine protected areas.

REFERENCES

AAAS. 2001. World Land Use. American Association for the Advancement of Science. http://www.ourplanet.com/aaas/pages/population01.html (10/02/03).

Alexander, M. 1977. *Introduction to Soil Microbiology*. New York: John Wiley & Sons.

Allee, W.C., A.E. Emerson, O. Park, et al. 1949. *Principles of Animal Ecology*. Philadelphia, PA: Saunders.

Allen, D.C. 2003. Biological diversity—Is variety the spice of life? http://www.dec.state.ny.us/website/dif/privland/forprot/health/nyfo/biodiv.pdf (10/18/03).

Anok and Peace. 2003. Overpopulation. Anok and peace. Cols, Ohio. http://noleaders.net/anok/features/nopop/ (10/02/03).

Arnold, G.W. 1983. The influence of ditch and hedgerow structure, length of hedgerows, and area of woodland and garden on bird numbers on farmland. *Journal of Applied Ecology* 20: 731–750.

Aude, E., K. Tybirk, and M.B. Pedersen. 2003. Vegetation diversity of conventional and organic hedgerows in Denmark. *Agriculture Ecosystems and Environment* 99: 135–147.

Avian Ecology. 2003. Avian ecology. http://www.ornithology.com/lectures/Avian%20Ecology.html (10/17/03).

Beetz, C.A. 2001. *Sustainable Pasture Management. Livestock Systems Guide*. October 2001. Fayetteville, AR: University of Arkansas.

Brown, L.R. 2001. *Paving the Planet: Cars and Crops Competing for Land*. Washington, D.C.: Earth Policy Institute.

CGIAR. 2003. Agroforestry—Combining nature and livelihoods. Consultative Group on International Agricultural Research. http://www.futureharvest.org/earth/agroforestry.html (11/03/03).

Chape, S., S. Blyth, L. Fish, et al. 2003. United Nations List of Protected Areas. World Conservation Monitoring Centre.

Clark, D.A., M.G. Lambert, and D.A. Grant. 1986. Influence of fertilizer and grazing management on North Island moist hill country. 5. Animal production. *New Zealand Journal of Agricultural Research* 26: 95–108.

Comba, L. and S. Corbet. 1998. Living larders for bumblebees. *Plantlife Magazine, Summer Issue*. 3 pp.

Conservation Issues. 2003. Impacts on biodiversity. Population growth, overconsumption and technology. http://www.redpath-museum.mcqill.ca/Qbp/3.Conservation/impacts.htm (11/16/03).

Daily, G.C., P.R. Ehrlich, and G.A. Sanchez-Azonfeifa. 2001. Countryside biogeography: Utilization of human dominated habitats by the avifauna of southern Costa Rica. *Ecological Applications* 11: 1–13.

Deforestation. 2003. Deforestation. http://www.bsrsi.msu.edu/rfrc/deforestation.html (10/04/03).

Dennis, C. 2002. Reef under threat from “bleaching outbreak.” *Nature* 415: 947.

Dirzo, R. and P.H. Raven. 2003. Global state of biodiversity and loss. *Annual Review of Environmental Resources* 28: 137–167.

Do or Die. 2003. Biodiversity and its loss—What does it all really mean? *Do or Die Issue* 8: 109–120 (available http://www.eco-action.org/dod/no8/biodiversity.html).

Doran, J.W. and T.B. Parkin. 1994. Defining and assessing soil quality. In J.W. Doran, D.F. Bezdicek, D.C. Coleman, and B.A. Stewart (eds.), *Defining Soil Quality for a Sustainable Environment*, pp. 3–21. Special Publication. No. 35. Madison, WI: Soil Science Society of America.

Dorworth, D. 2002. The new politics: developer vs. ecologists. Ketchum, ID: *Idaho Mountain Express and Guide*. September 25–October 1, 2002. 5 pp.

Dourojeanni, M.J. 1990. Entomology and biodiversity conservation in Latin America. *American Entomologist* 36(2): 88–93.

Dover, N. and L. Talbot. 1987. *To Feed the Earth: Agroecology for Sustainable Development*. Washington, D.C.: World Resources Institute.

Earle, S.A. 1995. *Sea Change: A Message of the Oceans*. New York: Putman's Sons.

Earthscan. 2002. *Global Environment Outlook 3: Past, Present and Future Perspectives*. United Nations Environmental Programme. London: Earthscan Publications.

Edwards, R. 1998. Save our pathogens. *New Scientist*. p. 5, 22. August 1998.

Edwards, C.A. and P.J. Bohlen. 1996. *Biology and Ecology of Earthworms*. London: Chapman & Hall.

Elton, C.S. 1927. *Animal Ecology*. London: Sidgwick and Jackson, Ltd.

Environmental Threats. 2003. Why we need the 1% alliance. Top 10 environmental threats. http://www.onepercentfortheplanet.org/threats.html (11/16/03).

ERAB. 1981. *Biomass Energy*. Washington, D.C.: Energy Research Advisory Board, U.S. Department of Energy.

Erwin, T. 1983. Beetles and other insects of tropical forest canopies at Manaus, Brazil, sampled by insecticide fogging tropical rainforest. In *Tropical Rainforest: Ecology and Management*. S. Sutton (ed.), pp. 59–75. Oxford, England: Blackwell Scientific.

ESA. 2003. *ESA Position Statement on Insects and Biodiversity*. Lanham, MD: Entomological Society of America. 4 pp.

Ewel, J.J. 1986. Designing agricultural ecosystems for the humid tropics. *Annual Review of Ecology and Systematics* 17: 245–271.

Faeth, P. and P. Crosson. 1994. Building the case for sustainable agriculture. *Environment* 36(1): 16–20.

FAO. 2002a. *Food Balance Sheets*: *A Handbook*. Rome: United Nations, Food and Agricultural Organization.

FAO. 2002b. *World Agriculture: Towards 2015/2030*. Summary report prepared mainly by Paul Harrison. Rome: United Nations, Food and Agriculture Organization.

FAO. 2003a. *Why Should Soil Biodiversity be Managed and Conserved?* Land and Water Development Division. Rome: United Nations, Food and Agriculture Organization. 9 pp.

FAO. 2003b. *Overview of Fish Production, Consumption and Trade: Based on 2001 Data*. United Nations, Food and Agriculture Organization. Fisheries Information, Data and Statistics Unit, May 2003.

FAO. 2004. *Biological Diversity in Food and Agriculture*. United Nations, Food and Agricultural Organization. http://www/fao/org/biodiversity/index.asp (1/10/04).

Fenster, C.R. 2003. *Protect Soil with Vegetative Residues*. Published by Cooperative Extension, Institute of Agriculture and Natural Resources. Lincoln, NB: University of Nebraska.

Fletcher, S.R. 1995. *Biological Diversity: Issues Related to the Convention on Biodiversity*. Washington, D.C.: National Council for Science and the Environment. 9 pp.

Fortin, M.C., J. Culley, and M. Edwards. 1994. Soil water. Plant growth and yield of strip-cropped corn. *Journal of Production Agriculture* 7: 63–69.

Francis, C.A., A. Jones, K. Crookston, et al. 1986. Strip cropping corn and grain legumes: A review. *American Journal of Alternative Agriculture* 1: 159–164.

Fritts, T.H. and G.H. Rodda. 1998. The role of introduced species in the degradation of island ecosystems: a case history. *Annual Review of Ecology and Systematics* 29: 113–140.

Goldberg, R., M. Elliott, and R. Naylor. 2001. *Marine Aquaculture in the U.S.: Environmental Impacts and Policy Options*. Pew Oceans Commission Report.

Gomez-Pompa, A. 2004. The role of biodiversity scientists in a troubled world. *BioScience* 54: 217–225.

Goreau, T., T. McClanahan, R. Hayes, et al. 2000. Conservation of coral reefs after the 1998 global bleaching event. *Conservation Biology* 14: 5–15.

Griffith, D.M. 2000. Agroforestry: A refuge for tropical biodiversity under fire. *Conservation Biology* 14: 325–326.

Hansen, J., M. Oppenheimer, M. Pearl, et al. 1996. *Panel Discussion: Extirpated Species, Warming Temperatures, and Politics Worry Scientists*. Columbia Forum on the Environment. New York: Columbia University.

Harder, B. 2003. Sea burial for Canada's cod fisheries. *Science News*. Washington. 163(May 17, 20): 318.

Hayes, W.A. 1996. *Understanding Wind Erosion and Its Control*. Cooperative Extension, Institute of Agriculture and Natural Resources. Lincoln, NB: University of Nebraska. 3 pp.

Henry, D. 2001. *Population Growth Fuels Biodiversity Loss*. SE-QLD Branch, Media Release. Cleveland, Qld. Sustainable Population Australia.

Hinrichsen, D. 1998. *Coastal Waters of the World: Trends, Threats, and Strategies*. Washington, D.C.: Island Press.

HMSO. 1995. *Biodiversity: The UK Steering Group Report. Volume 2: Action Plans*. London: Her Majesty's Stationary Office.

Homer-Devine, M.C., G.C. Daily, P.R. Ehrlich, et al. 2003. Countryside biogeography of tropical butterflies. *Conservation Biology* 17: 168–179.

IPGRI. 2004. *The Home Gardens Case Study*. Submitted by International Plant Genetic Resources Institute to Convention on Biological Diversity/United Nations Environmental Programme. http://www.ipgri.cgiar.org/themes/human/Articles/CBDCaseStudy.doc (1/10/04).

IUCN. 2002a. Plant species in trouble. IUCN, The World Conservation Union. http://www.iucn.org (11/22/03).

IUCN. 2002b. 2002 IUCN Red list of threatened species. IUCN, The World Conservation Union. http://www.redlist.org (10/01/03).

IUCN. 2004. Species extinction. IUCN, The World Conservation Union. http://iucn.org (02/22/04).

James, C. 1999. Global status and distribution of commercial transgenic crops in 1997. *Biotechnology and Development Monitor, No. 35*. June 1999.

Kedziora, A., J. Olejnik, and J. Kapuchinski. 1989. Impact of landscape structure on heat and water balance. *International Association for Ecology* 17: 1–17.

Kidd, C. and D. Pimentel. 1992. *Integrated Resource Management: Agroforestry for Development*. San Diego, CA: Academic Press.

Krajick, K. 2001. Arctic life on thin ice. *Science* 291: 424–425.

Krajick, K. 2004. All downhill from here? *Science* 303: 1600–1602.

LaSalle, J. and I.D. Gould. 1993. Hymenoptera: Their diversity and their impact on the diversity of other organisms. In J. Lasalle and I.D. Gould (eds.), *Hymenoptera and Biodiversity*, pp. 1–26. Oxon, UK: CAB International.

Lavelle, P. and A.V. Spain. 2001. *Soil Ecology*. Dordrecht: Kluwer Academic Publishers.

Leakey, R.R.B. 1997. Agroforestry for biodiversity in farming systems. In W. Collins and C. Qualset (eds.), *Biodiversity in Agroecosystems*, pp. 127–145. New York: Lewis Publishers.

Lu, Y. and Lu, J. 2003. *Oasis Forestry in Xinjiang. Agroforesty Systems in China*. Ottawa, Canada. International Development Research Centre. 5 pp.

MacFadyen, A. 1961. Metabolism of soil invertebrates in relation to soil fertility. *Annals of Applied Biology* 49: 215–218.

Machlis, G.E. and D.L. Tichnell. 1985. *The State of the World's Parks.* Boulder, CO: Westview Press.

Masyuk, N.P. 2002. The genus *Chlamydomonas* HER. In the flora of Ukraine. *International Journal of Algae* 4(1)*:* 1–17.

McIntyre, S. 2001. *Incorporation of Practical Measures to Assist Conservation of Biodiversity within Sustainable Beef Production in Northern Australia.* (CSIRO) Commonwealth Scientific and Industrial Research Organization. *Sustainable Ecosystems.* Australia. 3 pp.

Metting, F.B. 1993. *Soil Microbial Ecology.* New York: Marcel Dekker, Inc.

Mishra, U. and D.W. Dhar. 2004. *Biodiversity and Biological Degradation of Soil. National Center for Conservation and Utilization of Blue-Green Algae.* Indian Agricultural Research Institute. New Delhi, India. 8 pp.

Morin, N. 1995. Vascular plants in the United States. Missouri Botanical Garden. http://biology.usgs.gov/s+t/nopframe/j084.htm (10/16/03).

Moore, J.A. 2002. *Climate Change and Extreme Weather-Related Event Results.* Southern Forest Resource Assessment. USDA Forest Service. 4 pp.

Muriuki, J.N. 2003. *Co-operation or Conflict? Managing Scarce Resources of Africa. A Case of Community-Wildlife Conservation in Kenya.* Kenyatta University, Kenya 8 pp.

Myers, N. 2002. Biodiversity and biodepletion: The need for paradigm shift. In T. O'Riordan and S. Stoll (eds.), *Protecting the Protected: Managing Biodiversity for Sustainability,* pp. 46–60. Cambridge, UK: Cambridge University Press.

Myers, N. 2003a. The last extinction? *Foreign Policy,* March/April. 2 pp.

Myers, N. 2003b. Earth's top environmental problems. Population press. http://www/popco.org/press/articles/2003-1-myers.html (1/10/04).

Myers, R.A. and B. Worm. 2003. Rapid worldwide depletion of predatory fish communities. *Nature* 423: 6937.

NAS. 1988. *Biodiversity.* Washington, D.C.: National Academy of Sciences.

NAS. 2000. *Importance of Pesticides.* Washington, D.C.: National Academy of Sciences.

NAS. 2003. *Frontiers in Agricultural Research: Food, Health, Environment, and Communities.* Washington, D.C.: National Academy of Sciences.

Native Pollinator. 2003. Native pollinator and native plant demonstration project. http://www.denis.osd.mil/denix/Public/ES-Programs/Conservation/Legacy/Native_Pollinator_Native_Plant_Demo.pdf (11/13/03). 46 pp.

Neveln, V. 2003. Organic mulch: Helpful or harmful. *Garden and Hearth* 2001–2003. Editors@gardenandhearth.com. 5 pp.

Nobel, I.R. and R. Dirzo. 1997. Forests as human-dominated ecosystems. *Science* 277: 522–525.

Novacek, M. 2001. *The Biodiversity Crisis: Losing What Counts.* New York: American Museum of Natural History, New Press.

Oka, I.N. 1991. Success and challenges of the Indonesian national integrated pest management program in the rice based cropping system. *Crop Protection* 10: 163–165.

Olah-Zsupos, A. and B. Helmeczi. 1987. The effect of soil conditioners on soil microorganisms. In J. Szegi (ed.), *Soil Biology and Conservation of the Biosphere.* Vols. 1–2, pp. 829–837. *Proceedings of the 9th International Symposium.* Budapest: Akademiai Kiado.

Ontario. 1987. *Soil Erosion Causes and Effects.* Ottawa, Ontario: Ontario Ministry of Agriculture and Food.

Osler, G.H.R. and A.J. Beattie. 2002. Contribution of orbatid and messtigmatid mites in ecologically based estimates of global species richness. *Austral Ecology* 26(1): 70–79.

Paoletti, M.G. 1999a. The role of earthworms for assessment of sustainability and as bioindicators. *Agriculture, Ecosystems and Environment* 74: 137–156.

Paoletti, M.G. (ed.) 1999b. *Invertebrate Biodiversity as Bioindicators of Sustainable Landscapes. Practical Use of Invertebrates to Assess Sustainable Landuse.* Amsterdam: Elsevier.

Paoletti, M.G., M.R. Favretto, S. Ragusa, et al. 1989. Animal and plant interactions in the agroecosystems: The case of the woodland remnants in northeastern Italy. *Ecological International Bulletin* 17: 79–91.

Parol, A. 1986. The productivity of cultivated pastures evaluated by dairy cows depending on the botanical composition and fertilization. *Bioproduction of Grasslands.* Tallinn, Estonia, 141–148.

Parol, A. 2003. *The Importance of White Clover in Pasture to the Productivity of Dairy Cows.* Institute of Grassland Science and Botany, Estonia Agricultural University. Tartu, Estonia. 5 pp.

Pauly, D. and R. Watson. 2003. Counting the last fish. *Scientific American* 289(1): 42–47.

Pauly, D., V. Christiensen, J. Dalsgaard, et al. 1998. Fishing down marine food webs. *Science* 279(5352)*:* 860–863.

PCC. 2002. News Bites. http://www.pccnaturalmarkets.com/sc/0205/newsbites.html (1/19/03).

Perfecto, I., R.A. Rice, R. Greenberg, et al. 1996. Shade coffee: A disappearing refuge for biodiversity. *BioScience* 46: 598–608.

Pimentel, D. 1997. *Techniques for Reducing Pesticides: Environmental and Economic Benefits.* Chichester, UK: John Wiley.

Pimentel, D. 2002. *Biological Invasions: Economic and Environmental Costs of Alien Plant, Animal, and Microbe Species.* Boca Raton, FL: CRC Press.

Pimentel, D. 2005. Environmental and economic costs of the application of pesticides primarily in the United States. *Environment, Development and Sustainability* 7: 229–252.

Pimentel, D. and M. Pimentel. 1996. *Food, Energy and Society.* Rev. edition. Niwot, CO: University Press of Colorado.

Pimentel, D. and M. Pimentel. 2003. World population, food, natural resources and survival. *World Futures* 59: 145–167.

Pimentel, D. and D. Wen. 2004. China and the world: population, food and resource scarcity. In T.C. Tso and H. Kang (eds.), *Dare to Dream: Vision of 2050 Agriculture in China*, pp. 103–116. Beijing: China Agricultural University Press.

Pimentel, D. and A.G. Wheeler. 1973. Species diversity of arthropods in the alfalfa community. *Environmental Entomology* 2(4): 659–668.

Pimentel, D., U. Stachow, D.A. Takacs, et al. 1992. Conserving biological diversity in agricultural/forestry systems. *BioScience* 42: 354–362.

Pimentel, D., L. McLaughlin, A. Zepp, et al. 1993. Environmental and economic impacts of reducing agricultural pesticide use. In D. Pimentel (ed.), *Pesticide Question: Environment, Economics and Ethics*, pp. 223–278. New York: Chapman & Hall.

Pimentel, D., C. Wilson, C. McCullum, et al. 1997. Economic and environmental benefits of biodiversity. *BioScience* 47(11): 747–758.

Pimentel, D., O. Bailey, P. Kim, et al. 1999. Will the limits of the Earth's resources control human populations? *Environment, Development and Sustainability* 1: 19–39.

Pimentel, D., L. Lach, R. Zuniga, et al. 2000. Environmental and economic costs of nonindigenous species in the United States. *BioScience* 50(1): 53–65.

Pimentel, D., B. Berger, D. Filiberto, et al. 2004a. Water Resources: Agricultural and environmental issues. *BioScience* 54(10): 909–918.

Pimentel, D., A. Pleasant, J. Barron, et al. 2004b. U.S. energy conservation and efficiency: Benefits and costs. *Environment Development and Sustainability* 6: 279–305.

Pimentel, D., R. Zuniga, and D. Morrison. 2005a. Update on the environmental and economic costs associated with alien invasive species in the United States. *Ecological Economics* 52: 273–288.

Pimentel, D., P. Hepperly, J. Hanson, et al. 2005b. Environmental, energetic and economic comparisons of organic and conventional farming systems. *BioScience* 55(7): 573–582.

Pimm, S.L. 1991. *The Balance of Nature: Ecological Issues in the Conservation of Species and Communities*. Chicago, IL: University of Chicago Press.

Pimm, S.L. 2002. *Food Webs.* Chicago, IL: University of Chicago Press.

Pimm, S.L. and J.H. Brown. 2004. Domains of diversity. *Science* 304: 831–833.

Pimm, S.L., G.J. Russell, J.L. Gittlemand, et al. 1995. The future of biodiversity. *Science* 269: 347–350.

PRB. 2003. *World Population Data Sheet.* Washington, D.C.: Population Reference Bureau.

Price, P.W. 1988. An overview of organismal interactions in ecosystems in evolutionary and ecological time. *Agriculture, Ecosystems and the Environment* 24: 369–377.

Rainforest. 2003. Rainforest Live. Information pages http://www.rainforestlive.org.uk/index.cfm?articleid=214 (10/06/03).

Ramert, B. 2002. The use of mixed species cropping to manage pests and diseases—theory and practice. In J. Powell, G. Davies, S. Fowler, et al. (eds.), *U.K. Organic Research. Proceedings of the Colloquium for Organic Research 2002*, pp. 207–210. Conference 26–28, March 2002, Aberystwth.

Ramsar. 2000. *Background Papers on Wetland Values and Functions. The Ramsar Convention on Wetlands*. Gland, Switerland: Ramsar Convention Bureau.

Reid, W.V. and K.R. Miller. 1989. *Keeping Options Alive: The Scientific Basis for Conserving Biodiversity.* Washington, D.C.: World Resources Institute.

Richards, B.N. 1974. *Introduction to the Soil Ecosystem.* New York: Longman.

Ricketts, T.H. 2001. The matrix matters: Effective isolation in fragmented landscapes. *The American Naturalist* 158: 87–99.

Robbins, J. 2001. *The Food Revolution: How Your Diet Can Help Your Life and Our World.* Berkeley, CA: Conari Press.

Roberts, C., J.A. Bohnsack, F. Gell, et al. 2001. Effects of marine reserves on adjacent fisheries. *Science* 294: 1920–1923.

Rodriguez, A.S.L., S.J. Andelman, M.I. Bakarr, et al. 2003. Global gap analysis: Towards a representative network of protected areas. *Advances in Applied Biochemistry Science* 5(August): 3–98.

Rotational Grazing. 2004. Protect soil with rotational grazing. http://www.thisland.uiuc.edu/60ways_10.html (1/12/04).

Rushton, S.P., M.L. Luff, and M.D. Eyre. 1989. Effects of pasture improvement and management on the ground beetle and spider communities of upland grasslands. *Journal of Applied Ecology* 26: 489–503.

Sala, O.E., F.S. Chapin, J.J. Armesto, et al. 2000. Global biodiversity scenarios for the year 2100. *Science* 287: 1770–1774.

Schroth, G., U. Krauss, L. Gasparotto, et al. 2000. Pests and diseases in agroforestry systems of the humid tropics. *Agroforestry Systems* 50(3): 199–241.

Sigvald, R. and J. Yuen. 2001. *Cereal/Legume Intercropping Systems: Effect on the Associate Crop Pathosystems*. Swedish University of Agricultural Sciences, Department of Ecology and Plant Production Science/Integrated Pest Management, P.O. Box 7043, 75007 Uppsala, Sweden. 2 pp.

Soil Organisms. 2004. Soil Organisms. http://www.biodiversity.org.uk.ibs/envmath/resources/year3/env324/pro (1/10/04).

Stock, N.E. 1988. Insect diversity: Facts, fiction and speculation. *Biological Journal of Linnaean Society* 35: 321–337.

Streams for the Future. 2004. Classic Stream Problems; New Stream Solutions. Streams for the Future, Fisheries Division, Missouri Department of Conservation, Jefferson City, MO. 7 pp.

Sugden, A.M. and G.F. Rands. 1990. The ecology of temperate cereal fields. *Trends in Ecology and Evolution* 5: 205–206.

Swing, J.T. 2003. What future for the oceans? *Foreign Affairs* 82(5): 139–152.

Taddese, G. 2001. Land degradation: A challenge to Ethiopia. *Environment Management* 27(6): 815–824.

Terborgh, J.W. 1988. The big things that run the world: A sequel to E.O. Wilson. *Conservation Biology* 2: 402–403.

Thimmayya, A. 1998. The effects of fertilization on soil and litter fauna in oak forest. http://www.courses.mbl.edu/SES/data/project/1998/thimmayya.pdf (3/29/04).

Thomas, C.D., A. Cameron, R.E. Green, et al. 2004. Extinction risks from climate change. *Nature* 427: 145–148.

Thomas, D.S.G. and N.J. Middleton. 1993. Salinization: New perspectives on a major desertification issue. *Journal of Arid Environments* 24: 95–105.

Thorne-Miller, B. and J. Cantena. 1991. *The Living Ocean: Understanding and Protecting Marine Biodiversity.* Washington, D.C.: Island Press.

Thrupp, L.A. 1998. *Cultivating Diversity: Agrobiodiversity and Food Security.* Washington, D.C.: World Resources Institute.

Troeh, F.R., J.A. Hobbs, and R.L. Donahue. 1999. *Soil and Water Conservation.* Englewood Cliffs, NJ: Prentice Hall.

Tuxill, J. 1999. Nature's Cornucopia. Report No. 148. Washington, D.C.: World Watch Institute.

UNESCO. 2001. Protecting Ecosystems. World Water Assessment programme. Paris: United Nations Education Scientific and Cultural Organization.

UNESCO. 2002. Securing the Food Supply. World Water Assessment Programme. Paris: United Nations Education Scientific and Cultural Organization.

Uri, N. 2001. A note on soil erosion and its environmental consequences in the United States. *Water, Air, and Soil Pollution* 129: 181–197.

USBC. 2002. *Statistical Abstract of the United States 2002.* Washington, D.C.: U.S. Bureau of the Census, U.S. Government Printing Office.

USDA. 1999. *Agricultural Phosphorus and Eutrophication.* Washington, D.C.: Agricultural Research Service, U.S. Department of Agriculture.

USDA. 2002. *Agricultural Statistics.* Washington, D.C.: U.S. Department of Agriculture.

USGS. 2003. Birds as Indicators of Riparian Vegetation Condition in the Western U.S. U.S. Geological Society. Northern Prairie Wildlife Research Center. 3 pp.

Vandermeer, J., D. Lawerence, A. Symstad, et al. 2002. Effect of biodiversity on ecosystem functioning in managed ecosystems. In *Biodiversity and Ecosystem Functioning: Synthesis and Perspectives*, pp. 221–236. Oxford, UK: Oxford University.

Vietmyer, N. 1995. Applying biodiversity. *Journal of the Federation of American Scientists* 48(4): 1–8.

Wagner, T. 2003. Seasonality of canopy beetles in Uganda. In Y. Basset, V. Novotny, S.E. Miller, et al. (eds.), *Arthropods of Tropical Forests: Spatio-temporal Dynamics and Resource Use in the Canopy*, pp. 146–158. Cambridge, MA: Cambridge University Press.

Walter, H. 1985. *Vegetation of the Earth and Ecological Systems of the Geo-biosphere.* Berlin: Springer-Verlag.

Walter, K.S. and H.J. Gillett. 1998. *1997 IUCN Red List of Threatened Plants.* Compiled by the World Conservation Monitoring Centre. Cambridge, UK: IUCN/The World Conservation Union.

Warters, M.E. 1969. A Faunistic and Ecological Study of the Insects Found on the Corn Plant in Minnesota. Ph.D. Thesis, University of Minnesota, St. Paul, MN.

Wayne, L.G., D.J. Brenner, R.R. Colwell, et al. 1987. Report of the ad hoc committee on reconciliation of approaches to bacterial systematics. *International Journal of Systematic Bacteriology* 37(4): 463–464.

Western, D. 1994. Ecosystem conservation and rural development: the case in Amboseli. In D. Western, R.M. Wright, and S.C. Strum (eds.), *Natural Connection: Perspectives in Community-Based Conservation*, pp. 15–53. Washington, D.C.: Island Press.

Western, D. and M.C. Pearl. 1989. *Conservation for the Twenty-first Century.* New York: Oxford University Press.

Westman, W.E. 1990. Managing for biodiversity. *BioScience* 40: 26–33.

Whalon, D. 2002. *Integrated Crop Management in Apples.* East Lansing, MI: Clarksville Horticultural Research Station, Michigan State University. 5 pp.

Whitcomb, W.H. and K.E. Godfrey. 1991. The use of predators in insect control. In D. Pimentel (ed.), *Handbook of Pest Management in Agriculture*, Vol. II, pp. 215–241. Boca Raton, FL: CRC Press.

WHO. 2000. Malnutrition worldwide. World Health Organization. http://www.who.int/nut/malnutrition_worldwide.htm (July 27, 2000).

Wiebe, K. 1997. Resources, Sustainability, and Food Security. Food Security Assessment, International Agriculture and Trade Report No. GFA-9, pp. 36–42. Updated: April 24, 2002.

Wilson, E.O. 1987. The little things that run the world. *Conservation Biology* 1: 344–346.

Wilson, E.O. (ed.) 1988. *Biodiversity.* Washington, D.C.: National Academy of Sciences.

Wilson, E.O. 2003. Conserving biodiversity: A global view. *BirdScope* 17(4): 3–4.

World Bank. 2002. World Bank approves new forest policy and strategy. Increasing livelihoods for poor people while better protecting forests. The Board of Executive Directors. Washington, D.C.: The World Bank. 5 pp.

World Wildlife Fund. 1999. America's Global Warming Solutions. Study prepared for World Wildlife Fund and Energy Foundation. Tellus Institute: Resource and Environmental Strategies. August 1999. pp. 1–43.

WRI. 2002. Mechanisms for the loss of biodiversity. World Resources Institute. http://www.wri.org/diodiv/b05-gbs.html (2/1/04).

Wright, D.H. 1983. Species-energy theory: An extension of species-area theory. *Oikos* 41: 496–506.

Xerces Society. 2001. Why are invertebrates important? The Xerces Society. http:// exerces.org/why_conserve_inverts.htm (10/23/03).

Yohn, C.W. and E.B. Rayburn. 2004. Forage Management. Morgantown, WV: West Virginia University Extension Service. 4 pp.

17 Food Processing, Packaging, and Preparation

FOOD PROCESSING

Ever since humans first controlled fire, they have used its heat to cook some of their foods. Cooking, either by roasting, baking, steaming, frying, broiling, or boiling, makes many foods more palatable. Indeed, cooking enhances the flavor of foods such as meat; it also improves the flavor and consistency of many cereals and makes their carbohydrate content more digestible. Although not all vegetables are cooked before eating, the heating process if carefully done makes them more tender and yet preserves their natural colors and flavors. Certainly, cooking enables humans to have a wider variety of food on the dinner table. However, it can cause destruction of vitamin C, thiamine, and solubility losses of valuable minerals, especially if large amounts of water are used.

Heating has an even more important function than merely enhancing palatability characteristics. Heating food to 100°C or higher destroys harmful microbes, parasites, and some toxins that may be natural contaminants of food. *Staphylococcus* and *Salmonella* are destroyed by boiling, whereas *Clostridium botulinum* must be exposed to temperatures of 116°C (attained under pressure) if heat-resistant spores are to be eliminated. Another example is *Trichinella,* a small helminth (parasitic worm) found in uncooked pork. If consumed by humans, the worms migrate to human flesh, causing serious illness. But when pork is cooked to at least 58.5°C, the parasites are killed. Numerous harmful protozoans and worm parasites come from uncooked vegetables and fruits grown in gardens fertilized with human excreta. Although it is logical to associate such problems with primitive agriculture, they remain of concern in areas where organic gardening is not carefully practiced.

Except for grains and sugars, most foods humans eat are perishable. They deteriorate in palatability, spoil, or become unwholesome when stored for long periods. Surplus animal and crop harvests, however, can be saved for future use if appropriate methods of preservation are used. The major ways of preserving foods are canning, freezing, drying, salting, and smoking. With all methods the aim is to kill or restrict the growth of harmful microbes or their toxins and to slow or inactivate enzymes that cause undesirable changes in food palatability. For further protection during long periods of storage, preserved food is placed either in sterile metal cans or glass jars or frozen in airtight paper or plastic containers.

In many parts of the world, people continue to raise and preserve a large portion of their own food for use throughout the year, but in the West people rely heavily on fresh and commercially processed foods purchased in nearby supermarkets.

CANNING

Ever since Louis Pasteur proved that microbes, invisible to the eye, caused food to putrefy, various methods have been used to kill these harmful organisms. The basic process in canning is to heat the food to boiling point or higher under pressure, then pack and completely seal it in sterilized containers. The precise processing temperatures and times are dependent upon the acidity of the particular foodstuffs being processed. Foods with a slightly acidic pH (4.5 and higher) require the high heat of pressure canners to ensure safe processing. The density of the foodstuffs as well as the size and shape of the container also influence processing times.

The average energy input in commercial canning of vegetables and fruits is about 575 kcal/kg of food (Table 17.1). This figure represents only the energy expended in actual processing by heat and does not include the energy input required for making the container. (Packaging is discussed later in this chapter.) Canning vegetables in the home is much more energy intensive than commercial processing. For example, home-canned beans require 757 kcal/kg (Klippstein, 1979).

TABLE 17.1
Energy Inputs for Processing Various Products

Product	kcal/kg	Remarks
Beet sugar	5,660	Assumed 17% sugar in beets
Cane sugar	3,370	Assumed 20% sugar in cane
Fruit and vegetables (canned)	575	
Fruit and vegetables (frozen)	1,815	
Flour	484	Includes blending of flour
Baked goods	1,485	
Breakfast cereals	15,675	
Meat	1,206	
Milk	354	
Dehydrated foods	3,542	
Fish (frozen)	1,815	
Ice cream	880	
Chocolate	18,591	
Coffee	18,948	Instant coffee
Soft drinks	1,425	Per liter
Wine, brandy, spirits	830	Per liter
Pet food	828	
Ice production	151	

Source: After Casper, M.E., *Energy-Saving Techniques for the Food Industry*, Noyes Data Corp, Park Ridge, NJ, 1977.

FREEZING

In freezing, many of the desirable qualities of the fresh food are retained for relatively long periods of time. The temperatures employed, −18°C or lower, retard or prevent the growth of harmful microbes. Their growth is also inhibited by lack of water, which is frozen.

Fruits can be frozen dry with added dry sugar or in syrup. Vegetables must be blanched (boiled or steamed a short time) prior to freezing to inactivate plant enzymes that cause deterioration of natural flavors and colors. The energy input for freezing vegetables and fruits is significantly greater than that for canning, averaging 1815 kcal/kg of food frozen versus only 575 kcal/kg for canning (Table 17.1). The canning process requires only heating, whereas freezing may involve brief heating, cooling, and then actual freezing.

Furthermore, canned foods can be stored at room temperature (actually slightly cooler is recommended), whereas frozen food must be kept in freezers at temperatures of −18°C or lower. Maintaining such a low temperature requires about 265 kcal/kg/month of storage (USBC, 1975). The average energy input to store frozen foods in the home freezer is 1060 kcal/kg (Klippstein, 1979). Because frozen foods are usually stored about 6 months, this additional energy cost is significant, making the total energy input much greater than that for canning. However, the moisture-resistant plastic and paper containers for frozen foods require less energy to manufacture than the metal cans and glass jars used for canned food.

SALTING

Fish, pork, and other meats have been preserved by salting for more than 3000 years (Jensen, 1949). This food-processing method is not employed as widely today in developing countries as it has been in the past, perhaps because other methods make possible the preservation of a wider variety of foods.

Salt (NaCl) preserves fish and meat by dehydrating it and, more important, by increasing the osmotic pressure to a level that prevents the growth of microbes, insects, and other small organisms. Like sun-drying of foods in warm, sunny climates, salting requires a relatively small input of energy. Usually about 1 kg of salt is added per 4 kg of fish or meat (Hertzberg et al., 1973). The method requires an estimated 23 kcal/kg of fish or meat; additionally, 90 kcal of fossil energy is required to produce 1 kg of salt (Rawitscher and Mayer, 1977). Even so, the total energy input for salting is significantly lower than that required for freezing fish or meat.

The salted product can be stored in a cool, dry area or placed in a moisture-free container. Before the salted fish or meat can be eaten, it must be soaked and rinsed many times with fresh water to remove the salt. Then the fish or meat is usually cooked, but even after the soaking and the rinsing there is usually a sufficient residue to give the food a noticeably salty taste.

DRYING

Reducing the moisture level of grains, meats, legumes, and fruits to 13% or lower prevents the growth of harmful microbes and lessens chances for infestations by insects and other organisms. Sunlight, an effective source of energy for drying, has been used for centuries and is still used today, especially for such crops as fruits and legumes. It has the distinct advantage of being a continuous, unlimited energy source.

When not accomplished by the slow sun-drying method, drying becomes energy intensive because the removal of water requires large inputs of heat energy. For instance, removing 1 L of water from grains requires an average energy input of 3600 kcal (Leach, 1976). However, Leach (1976) reports that by using the most efficient technology available, it is possible to remove a liter of water from grains with an input of only 1107 kcal/L.

In investigating the drying of corn in the United States, Pimentel et al. (1973) reported an energy input of 1520 kcal/L of water removed. Put another way, 1520 kcal is expended to reduce the moisture level of 7.4 kg of field-harvested corn from 26.5 to 13%.

The average energy input used to dehydrate foods is 3542 kcal/kg (Table 17.1). Thus, the energy input for drying approximately equals the food energy contained in 1 kg of many typical grains (about 3400 kcal). For potato flakes, the energy input for drying can be as high as 7517 kcal/kg (Singh, 1986).

All these calculated energy inputs for removing moisture from foods are higher than the theoretical values for evaporation. For example, the evaporation of 1 L of water from an open container theoretically requires as little as 620 kcal of energy (HCP, 1974). However, two to six times more energy is generally required to dehydrate food because the water in the food is not as accessible as it is in an open dish and must be removed from inside the cells of vegetables, fruits, or meats. In other words, barriers must be overcome to remove the water from food, and this requires extra energy.

In freeze-drying, a recently developed technique, the food is first frozen, then dried under extremely low pressure. This makes it possible to attain a moisture content much lower than 13%; the resultant food is exceptionally light and can be stored at room temperature. However, this process is even more energy intensive than regular drying because it requires energy for both freezing and drying.

SMOKING

Smoking, like drying, originated in primitive societies yet is still used today. Fish, meats, and grains are the major foods preserved by this method. Smoking preserves food in two ways. First, the heat dries or dehydrates the food; second, the various tars, phenols, and other chemicals in the smoke are toxic to microbes and insects. Most of these chemicals are also carcinogenic to humans if consumed in large amounts.

In many developing countries, farm families hang grains from the ceiling of the kitchen, where the smoke and heat from the open fire both dry and smoke the stored grain. This simple processing and storage method minimizes insect and microbial growth.

To smoke 1 kg of thin strips of fish, about 1 kg of hardwood (such as hickory) is used. Adding sand to the hardwood chips keeps the fire smoldering during the smoking process. The energy input for smoked fish is estimated to be about 4500 kcal/kg, with all of the energy coming from the wood chips burned.

VARIOUS PROCESSED AND PREPARED FOODS

The energy inputs for preserved, processed, and home-prepared foods are substantial. For example, in an analysis of the energy inputs needed to produce a 1-kg loaf of white bread commercially in the United Kingdom, Leach (1976) reported that 77% of the 3795 kcal total energy used to produce the bread (including marketing costs) is used in processing, with 13% for milling and 64% for baking.

In the United States, producing a 1-kg loaf of white bread requires an input of 7345 kcal, substantially greater than that for the United Kingdom. Milling and baking account for only 27% of the total energy input, as compared with 77% in Leach's analysis (Figure 17.1). Of the 27%, 7% of the energy is for milling and 20% for baking, which is appreciably lower than the input for wheat production, and which in turn is 45% of the total energy input. Hence, the major energy input for the white bread produced in the United States is expended for wheat grain production, and it would appear that energy inputs for grain production for bread is appreciably lower than in the United States (Figure 17.1).

The energy inputs to produce a 455-g can of sweet corn differ greatly from those expended for a loaf of white bread. The energy for production of the corn itself amounts to little more than 10% of the total energy used (Figure 17.2). Most of the total energy input of 1322 kcal is for processing, in particular for the production of the steel can. The heat processing of the corn requires only 316 kcal, but the production of the can requires about 1006 kcal.

The other large input that must be included in the energy accounting for processed foods is the energy expended by the consumer shopping for the food. In the United States, food shopping usually requires the use of a 1000- to 3000-kg automobile. Based on an allocation of the weight of the corn and other groceries, it takes about 311 kcal—or about three-fourths the amount of energy expended to produce the corn

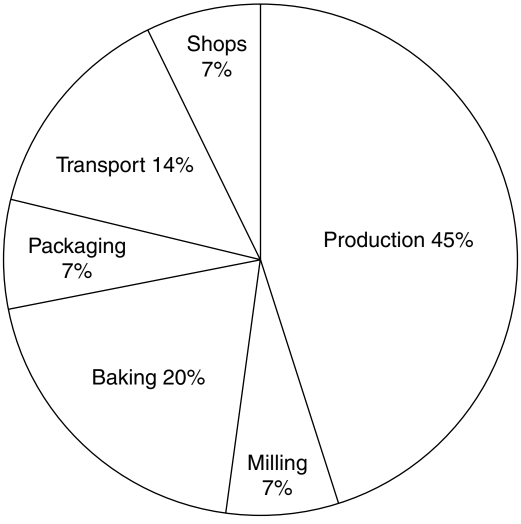

FIGURE 17.1 Percentages of total inputs (7345 kcal) for the production, milling, baking, transport, and shopping for a 1-kg loaf of bread.

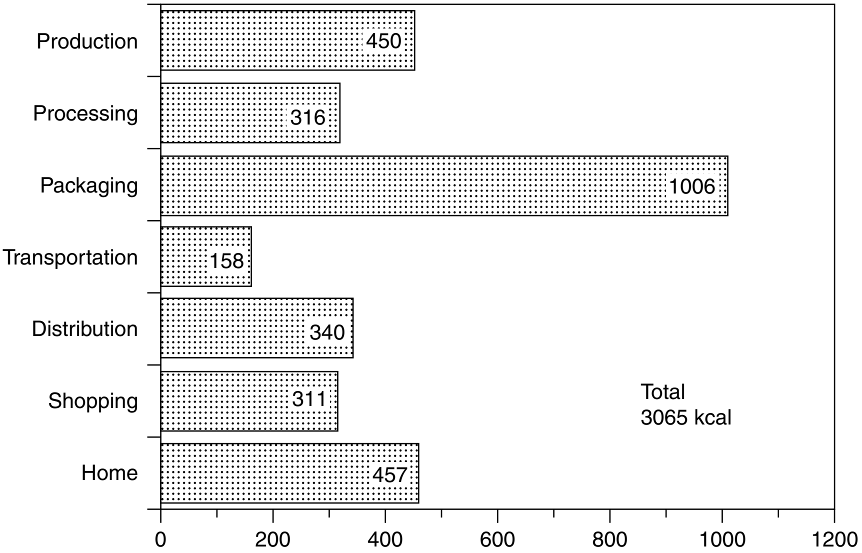

FIGURE 17.2 Energy inputs for a 455-g (375-kcal) can of sweet corn.

itself—to transport a 455-g can of corn home from the store. Energy expended in home preparation amounts to 457 kcal, or 12% of the total, and includes cooking the corn and using an electric dishwasher to clean the pots, pans, plates, and other utensils used.

All the energy inputs for producing, processing, packaging, transporting, and preparing a 455-g can of corn total 3065 kcal (Figure 17.2). Contrast that with the 375 kcal of food energy provided by the corn. Hence, about 9 kcal of fossil energy is necessary to supply 1 kcal of sweet corn food energy at the dinner table.

The pattern of energy inputs for beef differs greatly from that for sweet corn. Although 140 g of beef provides about 375 kcal of food energy, about 1000 kcal of fossil energy are expended just in the production of this amount of beef. The energy inputs for beef, including those for processing, transportation, and marketing, are all relatively small compared to the production inputs. The prime reason for the high production input is that large quantities of grain are fed to beef animals in the United States. Energy accounting of the U.S. food system is complicated by the fact that most of the corn and other cereal grains suitable for human consumption are fed to livestock.

The energy inputs for processing several other food products are presented in Table 17.1. The relatively large inputs for processing of 1 kg of sugar—3370 kcal for cane sugar and 5660 kcal for beet sugar—are due primarily to the energy used for the removal of water by evaporation, an energy-intensive process. Thus, 1 kg of crystalline sugar, which has a food energy value of 3850 kcal, requires almost that much energy to process the cane.

Breakfast cereals also require much energy to process and prepare—on the average, about 15,675 kcal/kg (Table 17.1). One kilogram of cereal contains about

3600 kcal of food energy. The energy inputs include those required for grinding, milling, wetting, drying, and baking the cereals. Other technologies such as extrusion are sometimes used, and these require additional large inputs of energy.

Both chocolate and coffee concentrates require energy-intensive food-processing techniques, including roasting, grinding, wetting, and drying. Processing of 1 kg of chocolate or coffee requires more than 18,000 kcal/kg (Table 17.1).

The energy inputs for soft-drink processing are high because of the pressurized systems employed to incorporate carbon dioxide (Table 17.1). A total of 1425 kcal is required per liter of soft drink produced. By way of comparison, the processing of milk requires only 354 kcal/L. A 12-ounce can of diet soda requires about 600 kcal for the soda but 1600 kcal for the aluminum can. Thus, a can of diet soda with 1 kcal of food energy requires a total of 2200 kcal of fossil energy to produce.

PACKAGES FOR FOODS

In general, processed foods must be stored in some type of container. For instance, 455 g of frozen vegetables are usually placed in a small paper box that requires an expenditure of approximately 722 kcal of energy to make (Table 17.2). By contrast, the same quantity (455 g) of a canned vegetable such as corn is placed in a steel can

TABLE 17.2
Energy Required to Produce Various Food Packages

Package	kcal
Wooden berry basket	69
Styrofoam tray (size 6)	215
Molded paper tray (size 6)	384
Polyethylene pouch (16 oz or 455 g)	559[a]
Steel can, aluminum top (12 oz)	568
Small paper set-up box	722
Steel can, steel top (16 oz)	1006
Glass jar (16 oz)	1023
Coca-Cola bottle, nonreturnable (16 oz)	1471
Aluminum TV dinner container	1496
Aluminum can, pop-top (12 oz)	1643
Plastic milk container, disposable (0.5 gallon)	2159
Coca-Cola bottle, returnable (16 oz)	2451
Polyethylene bottle (1 qt)	2494
Polypropylene bottle (1 qt)	2752
Glass milk container, returnable (0.5 gallon)	4455

[a] Calculated from data of Berry and Makino.

Source: After Berry, R.S. and Makino, H., *Technology Review*, 76, 1–13, 32–43, 1974.

that requires 1006 kcal to make (Table 17.2). The energy input for a glass jar for 455 g of vegetables is 1023 kcal, about the same as that used to produce a steel can (Table 17.2).

Thus, processing 455 g of corn and placing it into a steel can requires an input of about 1300 kcal of energy (Figure 17.2). About 1550 kcal is expended in freezing 455 g of corn and placing it in a cardboard box, and the food must be stored at 0°C or lower, requiring an energy expenditure of about 265 kcal/kg/month.

Although there is little difference between the energy inputs required for the production of steel cans and glass jars, aluminum soft-drink cans require significantly higher energy inputs. A 355-milliliter (ml) steel can for soft drinks requires an input of about 570 kcal; the same size aluminum can requires 1643 kcal, nearly three times as much energy (Table 17.2). A 355-ml aluminum can of soda contains about 150 kcal of food energy in the form of sugar, equivalent to about 10% of the energy expended in the production of the aluminum can.

Aluminum food trays commonly used to hold frozen TV dinners also require a large energy input. An average tray requires 1500 kcal to make (Table 17.2), often more energy than the food the tray holds (usually 800–1000 kcal). In addition, the diverse containers used to display fruits, vegetables, and meats in grocery stores require energy for production. Energy expenditures range from about 70 kcal for wood berry baskets to 380 kcal for molded paper trays (Table 17.2).

Because of increased concern about solid waste, the energy inputs of recycling milk and beverage bottles have been analyzed. A disposable plastic half-gallon milk container requires 2160 kcal for production, whereas a half-gallon glass container requires 4445 kcal (Table 17.2). The returnable glass container must be used at least twice for an energy saving to be realized. Actually, because added energy is expended to collect, transport, sort, and clean the reusable container, it takes about four recycles of each glass container to gain an advantage over disposable containers.

Like milk containers, returnable glass beverage bottles require more energy for production than do nonreturnable bottles (Table 17.2). A 16-ounce returnable soft-drink bottle requires about 2450 kcal for production, compared to about 1470 kcal for the same size nonreturnable bottle. Although two uses of the returnable bottle would more than offset the production energy input, when the energy costs of collecting, transporting, and cleaning the returnable bottles are factored in, about four recycles are necessary to gain an energy advantage. Of course, other considerations, such as the costs and the environmental pollution caused by nonreturnable containers, must be weighed along with energy expenditure before community policies can be decided upon.

COOKING AND PREPARING FOODS

Foods for human consumption are often cooked or reheated in the home, requiring an expenditure of energy. In the United States, an estimated 9000 kcal of fossil energy are used per person per day for home refrigeration, heating of food, dishwashing, and so forth. This averages out to an estimated 4700 kcal/kg of food prepared.

Depending on the food, the fuel used, the material of the cooking containers, the method of preparation, and the stove used, the energy input varies considerably. There appears to be little difference between the total energy expended for baking, boiling, or broiling a similar product, assuming that that exposure of the food to heat is optimal and that the cooking utensils allow for efficient heat transfer to the food itself. In addition to the shape and construction material of the cooking utensils, color also affects the transfer of heat and, therefore, overall cooking efficiency. A shiny aluminum pan reflects much heat and therefore is less efficient than one with a dark, dull surface or one made from glass. Furthermore, the nature of the food itself—fluid, viscous, or dense—will either slow or speed heat transfer and alter the amount of energy used in a particular process. These variables make it difficult to calculate the precise energy expenditure.

When the efficiency of the entire cycle of energy transfer is compared, a gas stove is more efficient than an electric stove. Gas and electricity from coal are used as fuel in residential stoves. Gas is mined, and about 10% of its energy potential is lost in production and transport. In transferring its heat energy to a product, it is 37% efficient, making overall efficiency of cooking with gas about 33% (100 × 0.9 × 0.37).

The process for electricity is more complicated than for gas. First, mining and transport reduce the energy potential of coal by 8%; 92% of the initial energy potential of the coal is available at the power plant for generation of electricity. Coal-heat conversion into electricity results in a recovery of 33% of the energy potential. The transmission electricity over power lines is 92% efficient, and transmission of electric heat to the product is 75% efficient. Thus, the overall efficiency of heat to the product is about 21% (100 × 0.92 × 0.33 × 0.92 × 0.75).

Less efficient than either electricity or gas is cooking with charcoal or wood over an open hearth, as is often done in developing countries. An open fire is 8–10% efficient in transmitting heat to the food. However, if the wood fire is carefully tended under the pot, the transfer of energy can be nearly 20%, which is nearly as efficient as using a small wood stove, which is from 20 to 25% efficient.

The following examples demonstrate the general inefficiency of cooking food over an open wood fire. It takes 600 kcal of heat energy to cook 1 kg of food, so a wood fire, at an efficiency rate of 10% for cooking, must produce 6000 kcal of energy. The food itself, if a grain-like rice, would contain 3500 kcal of food energy. Hence, nearly twice as much energy would be used to cook the food than the food itself contains.

In developing nations, cooking uses nearly two-thirds of the total energy expended in the food system and production the remaining one-third (Table 17.3). Almost all of the energy used for cooking in developing countries comes from renewable sources, primarily biomass (wood, crop residues, and dung).

A significant percentage of wood is converted into charcoal for a cooking fuel. Like wood fires, open charcoal fires are about 10% efficient in the transfer of heat energy to food. However, charcoal production is extremely energy intensive. Although charcoal apparently has a high energy content (7100 kcal/kg), 28,400 kcal of hardwood must be processed to obtain the 7100 kcal of charcoal, a conversion efficiency of only 25%. Therefore, charcoal heating has an overall energy transfer efficiency of

TABLE 17.3
Model of Annual per Capita Use of Energy in the Food System of Rural Populations in Developing Countries

	Fossil energy (kcal)	Renewable energy (kcal)	Total (kcal)
Production of food	130,000	490,000	620,000
Processing	15,000	20,000	35,000
Storage	5000	20,000	25,000
Transport	30,000	20,000	50,000
Preparation	20,000	1,250,000	1,270,000
Total	200,000	1,800,000	2,000,000

Sources: Pimentel, D., *Environmental Biology*, 74(1), 1974 and In *Enciclopedia della Scienza e della Tecnica*, Mondadori, Milan, 1976, 251–266; Pimentel, D. and Beyer, N., unpublished data at Cornell University, Ithaca, NY, 1976; RSAS, presented at Energy Conference, Aspenasgarden, October 27–31. Stockholm, Sweden, Royal Swedish Academy of Sciences 1975; Revelle, R., personal communication, University of California at San Diego, La Jolla, CA, 1986; and Ernst, E., *Fuel Consumption Among Rural Families in Upper Volta*, Upper Volta, Eighth World Forestry Congress, 1978.

only 2.5% (25% × 10%). Not only is cooking with charcoal an extremely inefficient and costly way to transfer energy, the use of charcoal for fuel also depletes forest and firewood supplies (Eckholm, 1976).

REFERENCES

Berry, R.S. and H. Makino. 1974. Energy thrift in packaging and marketing. *Technology Review* 76: 1–13, 32–43.

Casper, M.E. 1977. *Energy-Saving Techniques for the Food Industry*. Park Ridge, NJ: Noyes Data Corp.

Eckholm, E.P. 1976. *Losing Ground. Environmental Stress and World Food Prospects*. New York: Norton.

Ernst, E. 1978. *Fuel Consumption Among Rural Families in Upper Volta*. Upper Volta: Eighth World Forestry Congress.

HCP. 1974. *Handbook of Chemistry and Physics*. Cleveland, OH: The Chemical Rubber Co.

Hertzberg, R., B. Vaughan, and J. Greene. 1973. *Putting Food By*. Brattleboro, VT: Stephen Green Press.

Jensen, L.B. 1949. *Meat and Meat Foods*. New York: Ronald Press.

Klippstein, R.N. 1979. *The True Cost of Home Food Preservation*. Cornell University Information Bulletin No. 158. Ithaca, NY: Cornell University.

Leach, G. 1976. *Energy and Food Production*. Guildford, Surrey, UK: IPC Science and Technology Press Ltd.

Pimentel, D. 1974. Energy use in world food production. *Environmental Biology* 74(1).

Pimentel, D. 1976. Crisi energetica e agricoltura. In *Enciclopedia della Scienza e della Tecnica*, pp. 251–266. Milan: Mondadori.

Pimentel, D. and N. Beyer. 1976. Energy inputs in Indian agriculture. Unpublished data at Cornell University, Ithaca, NY.

Pimentel, D., L.E. Hurd, A.C. Bellotti, et al. 1973. Food production and the energy crisis. *Science* 182: 443–449.

Rawitscher, M. and J. Mayer. 1977. Nutritional outputs and energy inputs in seafoods. *Science* 198: 261–264.

Royal Swedish Academy of Sciences (RSAS). 1975. *Energy Uses*. Presented at Energy Conference, Aspenasgarden, October 27–31. Stockholm, Sweden: Royal Swedish Academy of Sciences.

Singh, R.P. 1986. Energy accounting of food processing operations. In R.P. Singh (ed.), *Energy in Food Processing*, pp. 19–68. Amsterdam: Elsevier.

U.S. Bureau of the Census (USBC). 1975. *Statistical Abstract of the United States 1975.* Washington, D.C.: U.S. Government Printing Office.

18 Transport of Agricultural Supplies and Foods

Transport is an essential component of all food systems, especially those in industrialized nations such as the United States, which have highly developed industrial complexes and intensive agricultural systems. They grow food crops in specialized regions most conducive to agricultural production (e.g., the corn belt of the United States). Industrial production sites are generally located near population centers and available power sources. Thus, harvested crops have to be transported to the cities and towns where industry is located, and machinery, fertilizers, pesticides, fuel, and other goods used in agricultural production have to be transported from urban areas to farms.

Transportation in the food system is more complex than just shipping food directly from the farm to homes. After being harvested, most food crops have to be processed and packaged, then transported to large wholesale distribution centers. From there, the packaged foods are shipped to retail stores located near population centers, where individuals purchase them and transport them home.

To account for the energy expended in this vast network, the energy inputs in transporting goods to the farm, raw agricultural products to the processors, produce to wholesale–retail markets, and food from the grocery to the home will be analyzed.

TRANSPORT OF AGRICULTURAL SUPPLIES AND GOODS TO THE FARM

An estimated 160 million ha of cropland are cultivated annually in the United States. About 100 billion kg of goods and supplies are transported to farms for use in agricultural production each year. On average, then, about 600 kg of goods and supplies must be transported to farms for each hectare cultivated.

The energy needed to move goods by truck is estimated at 1.2 kcal/kg/km (Table 18.1). This estimate is based on the fact that trucks require about 0.143 L of diesel fuel to transport 1 t for a distance of 1 km (Thor and Kirkendall, 1982). Moving goods by rail requires an estimated 0.32 kcal/kg/km (Table 18.1), about one-fourth of the energy expended in truck transport (Table 18.1). The energy and cost to transport goods by barge is only 0.10 kcal/kg/km, or one-third that of rail transport. As expected, air transport has the highest energy cost, 6.36 kcal/kg/km (Table 18.1), more than 60 times costlier than barge transport.

As noted, 600 kg of goods and supplies are transported to each farm hectare. Available data indicate that 60% of the goods are transported by rail, 40% by truck,

TABLE 18.1
Energy Needed to Transport 1 kg for a Distance of 1 km

Transport system	kcal/kg/km
Barge	0.10[a]
Rail	0.32[a]
Truck	1.20[a]
Air	6.36[b]

[a] Thor and Kirkendall (1982).

[b] Estimated.

and that the average distance these goods are transported is 1500 km (Smith, 1991). The energy input for the 60% of the goods transported by rail is about 173,000 kcal/ha, and the 40% transported by truck use 430,000 kcal/ha. Thus, transportation of farm goods requires a total energy input of 603,000 kcal/ha cultivated. Annually, then, an estimated 96×10^{12} kcal is expended to transport the 100 million tons of goods and supplies needed on U.S. farms.

TRANSPORT OF FOOD AND FIBER PRODUCTS FROM THE FARM

About 160 million ha of cropland are harvested annually, at an average of 4000 kg/ha. Thus, an estimated 640 million tons of food and fiber products are transported from the farm to various locations for eventual consumption.

About 41% of agricultural goods are transported by truck, 40% by rail, and 19% by barge (Thor and Kirkendall, 1982). The products are transported an average distance of 1000 km (Thor and Kirkendall, 1982). Based on this information, the transport of goods from the farm to cities and towns requires 348×10^{12} kcal of energy per year, or 640 kcal/kg.

Based on experience, families usually shop about three times per week. With each person on average consuming 1000 kg of food per year, and with three people in the average family, 19.3 kg of food is transported from the grocery store on each trip. The average round trip to the grocery is estimated to be 7.8 km, or nearly 5 miles. The average automobile today gets about 8.4 km/L (20 miles/gal). Based on these data, it takes about 684 kcal to transport 1 kg of food home from the grocery store. This is slightly more than the amount of energy invested to transport 1 kg of food from the farm to the city or town.

REFERENCES

Smith, F.A. 1991. *Transportation in America: Statistical Analysis of Transportation in the United States.* Waldorf, MD: Eno Transportation Foundation, Inc.

Thor, C. and E. Kirkendall. 1982. *Energy Conservation.* Manhattan, KS: Extension Engineering, Kansas State University.

19 Renewable Energy: Current and Potential Issues

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The United States faces energy shortages and increasing energy prices within the next few decades (Duncan, 2001). Coal, petroleum, natural gas, and other mined fuels provide 75% of U.S. electricity and 93% of other U.S. energy needs (USBC, 2001). On average, every year each American uses about 93,000 kWh, equivalent to 8000 L of oil, for all purposes, including transportation, heating, and cooling (USBC, 2001). About 12 kWh (1 L of gasoline) costs as much as $0.50, and this cost is projected to increase significantly in the next decade (Schumer, 2001).

The United States, having consumed from 82% to 88% of its proved oil reserves (API, 1999), now imports more than 60% of its oil at an annual cost of approximately $75 billion (USBC, 2001). General production, import, and consumption trends and forecasts suggest that within 20 years the United States will be importing from 80% to 90% of its oil. The U.S. population of more than 285 million is growing each year, and the 3.6 trillion kWh of electricity produced annually at a cost of $0.07 to $0.20 per kWh are becoming insufficient for the country's current needs. As energy becomes more scarce and more expensive, the future contribution of renewable energy sources will be vital (USBC, 2001).

Fossil fuel consumption is the major contributor to the increasing concentration of carbon dioxide (CO_2) in the atmosphere, a key cause of global warming (Schneider et al., 2000). Global warming reduces agricultural production and causes other biological and social problems (Schneider et al., 2000). The United States, with less than 4% of the world population, emits 22% of the CO_2 from burning fossil fuels, more than any other nation. Reducing fossil fuel consumption may slow the rate of global warming (Schneider et al., 2000).

Diverse renewable energy sources currently provide only about 8% of U.S. needs and about 14% of world needs (Table 19.1), although the development and use of renewable energy is expected to increase as fossil fuel supplies decline. Several different technologies are projected to provide the United States most of its renewable energy in the future: hydroelectric systems, biomass, wind power, solar thermal systems, photovoltaic systems, passive energy systems, geothermal systems, biogas,

TABLE 19.1
Fossil and Solar Energy Use in the United States and the World (in kWh and quads)

	United States		World	
Form of Energy	**kWh × 109**	**Quads**	**kWh × 109**	**Quads**
Petroleum	10,973.1	37.71[a]	43,271.7	148.70[b]
Natural gas	6431.1	22.10[a]	24,414.9	83.90[b]
Coal	6314.7	21.70[a]	27,295.8	93.80[b]
Nuclear power	2249.4	07.73[a]	6984.0	24.00[b]
Biomass	1047.6	03.60[a]	8439.0	29.00
Hydroelectric power	989.4	03.40[a]	7740.6	26.60[b]
Geothermal	93.1	00.32[b]	291.0	01.00
Biofuels (ethanol)	26.2	00.09[c]	52.4	00.18
Wind energy	11.6	00.04	232.8	00.80
Solar thermal	11.6	00.04	11.6	00.04
Photovoltaics	11.6	00.04	11.6	00.04
Total consumption	28,159.4	96.77	118,745.4	408.06

Note: A quad is a unit of energy equal to 1 quadrillion British thermal units.

[a] Adapted from USBC (2001).

[b] Adapted from DOE/EIA (2001).

[c] Adapted from Pimentel (2001).

ethanol, methanol, and vegetable oil. In this chapter, we assess the potential of these various renewable energy technologies for supplying the future needs of the United States and the world in terms of land requirements, environmental benefits and risks, and energetic and economic costs.

HYDROELECTRIC SYSTEMS

Hydropower contributes significantly to world energy, providing 6.5% of the supply (Table 19.1). In the United States, hydroelectric plants produce approximately 989 billion kWh (1 kWh = 860 kcal = 3.6 MJ), or 11% of the nation's electricity, each year at a cost of $0.02 per kWh (Table 19.2; USBC, 2001). Development and rehabilitation of existing dams in the United States could produce an additional 60 billion kWh/year (Table 19.3).

Hydroelectric plants, however, require considerable land for their water storage reservoirs. An average of 75,000 ha of reservoir land area and 14 trillion L of water are required per 1 billion kWh/year produced (Table 19.2; Pimentel et al., 1994; Gleick and Adams, 2000). Based on regional estimates of U.S. land use and average annual energy generation, reservoirs currently cover approximately 26 million ha of the total 917 million ha of land area in the United States (Pimentel, 2001). To develop the remaining best candidate sites, assuming land requirements similar to those in past developments, an additional 17 million ha of land would be required for water storage (Table 19.3). Despite the benefits of hydroelectric power, the plants cause

TABLE 19.2
Land Resource Requirements and Total Energy Inputs for Construction of Facilities That Produce 1 Billion kWh of Electricity per Year

Electrical Energy Technology	Land Required (ha)	Energy (input–output ratio)	Cost per kWh ($)	Life in Years
Hydroelectric power	75,000[a]	1:24	0.020[b]	30
Biomass	200,000	1:7	0.058[c]	30
Parabolic troughs	1,100[d]	1:5	0.070–0.090[e]	30
Solar ponds	5,200[f]	1:4	0.150	30
Wind power	13,700[g]	1:5[h]	0.070	30
Photovoltaics	2,800[i]	1:7[i]	0.120–0.200	30
Biogas	—[j]	1:1.7–3.3[k]	0.020[k]	30
Geothermal	30	1:48	0.064[l]	20
Coal (nonrenewable)	166[m]	1:8	0.030–0.050[n]	30
Nuclear power (nonrenewable)	31[m]	1:5	0.050	30
Natural gas (nonrenewable)	134[n]	1:8	0.030–0.050[n]	30

[a] Based on a random sample of 50 hydropower reservoirs in the United States, ranging in area from 482 to 763,000 ha (FERC 1984; ICLD 1988).

[b] Pimentel et al. (1994).

[c] Production costs based on 70% capacity factor (John Irving, Burlington Electric, Burlington, VT, personal communication, 2001).

[d] Calculated from DOE/EREN (2001).

[e] DOE/EREN (2001).

[f] Based on 4000-ha solar ponds plus an additional 1200 ha for evaporation ponds.

[g] From Smith and Ilyin (1991).

[h] Adapted from Nelson (1996).

[i] Calculated from DOE (2001).

[j] No data available.

[k] William Jewell, Cornell University, Ithaca, NY, personal communication, 2001.

[l] DOE/EIA (1991).

[m] Smil (1994).

[n] Bradley (1997).

major environmental problems. The impounded water frequently covers valuable, agriculturally productive, alluvial bottomland. Furthermore, dams alter the existing plants, animals, and microbes in the ecosystem (Ligon et al., 1995; Nilsson and Berggren, 2000). Fish species may significantly decline in river systems because of these numerous ecological changes (Brown and Moyle, 1993). Within the reservoirs, fluctuations of water levels alter shorelines, cause downstream erosion, change physiochemical factors such as water temperature and chemicals, and affect aquatic communities. Sediments build up behind the dams, reducing their effectiveness and creating another major environmental problem.

TABLE 19.3

Current and Projected U.S. Gross Annual Energy Supply from Various Renewable Energy Technologies, Based on the Thermal Equivalent and Required Land Area

	Current (2000)			Projected (2050)		
Energy technology	kWh × 109	Quads	Million hectares	kWh × 109	Quads	Million hectares
Biomass	1047.6	3.600[a]	75[b]	1455.0	5	102[b]
Hydroelectric power	1134.9	3.900[a]	26[c]	1455.0	5	33
Geothermal energy	87.3	0.300[a]	0.400	349.2	1.2	1
Solar thermal energy	<11.6	<0.040	<0.010	291.0	10	11
Photovoltaics	<11.6	<0.040	<0.010	3201.0	11	3
Wind power	11.6	0.040[a]	0.500	2037.0	7	8
Biogas	<0.3	<0.001	<0.001	145.5	0.5	0.01
Passive solar power	87.5	0.300[d]	0	1746.0	6	1
Total	2392.2	82.210	101.921	10,679.7	45.7	159.01

[a] USBC (2001).

[b] This is the equivalent land area required to produce 3 metric tons/ha, plus the energy required for harvesting and transport.

[c] Total area based on an average of 75,000 ha per reservoir area per 1 billion kWh/year produced.

[d] Pimentel et al. (1994).

BIOMASS ENERGY SYSTEMS

Although most biomass is burned for cooking and heating, it can also be converted into electricity. Under sustainable forest conditions in both temperate and tropical ecosystems, approximately 3 dry metric tons per hectare per year of woody biomass can be harvested sustainably (Birdsey, 1992; Repetto, 1992; Trainer, 1995; Ferguson, 2001). Although this amount of woody biomass has a gross energy yield of 13.5 million kcal, approximately 33 L of diesel fuel per hectare, plus the embodied energy, are expended for cutting and collecting the wood for transport to an electric power plant. Thus, the energy input–output ratio for such a system is calculated to be 1:22. The cost of producing 1 kWh of electricity from woody biomass is about $0.058, which is competitive with other systems for electricity production (Table 19.2). Approximately 3 kWh of thermal energy is expended to produce 1 kWh of electricity, an energy input–output ratio of 1:7 (Table 19.2; Pimentel, 2001). Per capita consumption of woody biomass for heat in the United States amounts to 625 kg per year. In developing nations, use of diverse biomass resources (wood, crop residues, and dung) ranges from 630 kg per capita (Kitani, 1999) to approximately 1000 kg per capita (Hall, 1992). Developing countries use only about 500 L of oil equivalents of fossil energy per capita, compared with nearly 8000 L of oil equivalents of fossil energy used per capita in the United States.

Woody biomass could supply the United States with about 1.5 × 1012 kWh (5 quads thermal equivalent) of its total gross energy supply by the year 2050, provided that approximately 175 million ha were available (Table 19.3). A city of 100,000 people using the biomass from a sustainable forest (3 t/ha/year) for electricity would require approximately 200,000 ha of forest area, based on an average electrical demand of slightly more than 1 billion kWh (electrical energy [e]) (860 kcal = 1 kWh) (Table 19.2).

The environmental effects of burning biomass are less harmful than those associated with coal, but more harmful than those associated with natural gas (Pimentel, 2001). Biomass combustion releases more than 200 different chemical pollutants, including 14 carcinogens and 4 cocarcinogens, into the atmosphere (Alfheim and Ramdahl, 1986; Godish, 1991). Globally, but especially in developing nations where people cook with fuelwood over open fires, approximately 4 billion people suffer from continuous exposure to smoke (World Bank, 1992; WHO/UNEP, 1993; Reddy et al., 1997). In the United States, wood smoke kills 30,000 people each year (EPA, 2002). However, the pollutants from electric plants that use wood and other biomass can be controlled.

WIND POWER

For many centuries, wind power has provided energy to pump water and to run mills and other machines. Today, turbines with a capacity of at least 500 kW produce most commercially wind-generated electricity. Operating at an ideal location, one of these turbines can run at maximum 30% efficiency and yield an energy output of 1.3 million kWh (e) per year (AWEA, 2000a). An initial investment of approximately $500,000 for a 500 kW capacity turbine (Nelson, 1996), operating at 30% efficiency, will yield an input–output ratio of 1:5 over 30 years of operation (Table 19.2). During the 30-year life of the system, the annual operating costs amount to $40,500 (Nelson, 1996). The estimated cost of electricity generated is $0.07/kWh (e) (Table 19.2).

In the United States, 2502 MW of installed wind generators produce about 6.6 billion kWh of electrical energy per year (Chambers, 2000). The American Wind Energy Association (AWEA, 2000b) estimates that the United States could support a capacity of 30,000 MW by the year 2010, producing 75 billion kWh (e) per year at a capacity of 30%, or approximately 2% of the annual U.S. electrical consumption. If all economically feasible land sites were developed, the full potential of wind power would be about 675 billion kWh (e) (AWEA, 2000b). Offshore sites could provide an additional 102 billion kWh (e) (Gaudiosi, 1996), making the total estimated potential of wind power 777 billion kWh (e), or 23% of current electrical use.

Widespread development of wind power is limited by the availability of sites with sufficient wind (at least 20 km per hour) and the number of wind machines that the site can accommodate. In California's Altamont Pass Wind Resource Area, an average of one 50 kW turbine per 1.8 ha allows sufficient spacing to produce maximum power (Smith and Ilyin, 1991). Based on this figure, approximately 13,700 ha of land is needed to supply 1 billion kWh/year (Table 19.2). Because the turbines themselves occupy only approximately 2% of the area, most of the land can be used for vegetables, nursery stock, and cattle (DP Energy, 2002; NRC, 2002). However, it may be impractical to produce corn or other grains because the heavy equipment used in this type of farming could not operate easily between the turbines.

An investigation of the environmental impacts of wind energy production reveals a few hazards. Locating the wind turbines in or near the flyways of migrating birds and wildlife refuges may result in birds colliding with the supporting towers and rotating blades (Kellet, 1990). For this reason, Clarke (1991) suggests that wind farms be located at least 300 m from nature reserves to reduce the risk to birds. The estimated 13,000 wind turbines installed in the United States have killed fewer than 300 birds per year (Kerlinger, 2000). Proper siting and improved repellant technology, such as strobe lights or paint patterns, might further reduce the number of birds killed.

The rotating magnets in the turbine electrical generator produce a low level of electromagnetic interference that can affect television and radio signals within 2–3 km of large installations (IEA, 1987). Fortunately, with the widespread use of cable networks or line-of-sight microwave satellite transmission, both television and radio are unaffected by this interference.

The noise caused by rotating blades is another unavoidable side effect of wind turbine operation. Beyond 2.1 km, however, the largest turbines are inaudible even downwind. At a distance of 400 m, the noise level is about 56 decibels (IEA, 1987), corresponding roughly to the noise level of a home airconditioning unit.

SOLAR THERMAL CONVERSION SYSTEMS

Solar thermal energy systems collect the sun's radiant energy and convert it into heat. This heat can be used directly for household and industrial purposes or to produce steam to drive turbines that produce electricity. These systems range in complexity from solar ponds to electricity-generating parabolic troughs. In the material that follows, we convert thermal energy into electricity to facilitate comparison with other solar energy technologies.

Solar Ponds

Solar ponds are used to capture radiation and store the energy at temperatures of nearly 100°C. Constructed ponds can be converted into solar ponds by creating a layered salt concentration gradient. The layers prevent natural convection, trapping the heat collected from solar radiation in the bottom layer of brine. The hot brine from the bottom of the pond is piped out to use for heat, for generating electricity, or both.

For successful operation of a solar pond, the salt concentration gradient and the water level must be maintained. A solar pond covering 4000 ha loses approximately 3 billion L of water per year (750,000 L/ha/year) under arid conditions (Tabor and Doran, 1990). The solar ponds in Israel have been closed because of such problems. To counteract the water loss and the upward diffusion of salt in the ponds, the dilute salt water at the surface of the ponds has to be replaced with fresh water and salt added to the lower layer.

The efficiency of solar ponds in converting solar radiation into heat is estimated to be approximately 1:4 (i.e., 1 kWh of input provides 4 kWh of output), assuming a 30-year life for the solar pond (Table 19.2). Electricity produced by a 100 ha (1 km^2) solar pond costs approximately \$0.15 per kWh (Kishore, 1993).

Some hazards are associated with solar ponds, but most can be avoided with careful management. It is essential to use plastic liners to make the ponds leakproof and prevent contamination of the adjacent soil and groundwater with salt. The degradation of soil quality caused by sodium chloride can be avoided by using an ammonium salt fertilizer (Hull, 1986). Burrowing animals must be kept away from the ponds by buried screening (Dickson and Yates, 1983).

Parabolic Troughs

Another solar thermal technology that concentrates solar radiation for large-scale energy production is the parabolic trough. A parabolic trough, shaped like the bottom half of a large drainpipe, reflects sunlight to a central receiver tube that runs above it. Pressurized water and other fluids are heated in the tube and used to generate steam, which can drive turbogenerators for electricity production or provide heat energy for industry.

Parabolic troughs that have entered the commercial market have the potential for efficient electricity production because they can achieve high turbine inlet temperatures (Winter et al., 1991). Assuming peak efficiency and favorable sunlight conditions, the land requirements for the central receiver technology are approximately 1100 ha per 1 billion kWh/year (Table 19.2). The energy input–output ratio is calculated to be 1:5 (Table 19.2). Solar thermal receivers are estimated to produce electricity at a cost of approximately $0.07–$0.09 per kWh (DOE/EREN, 2001).

The potential environmental impacts of solar thermal receivers include the accidental or emergency release of toxic chemicals used in the heat transfer system (Baechler and Lee, 1991). Water scarcity can also be a problem in arid regions.

PHOTOVOLTAIC SYSTEMS

Photovoltaic cells have the potential to provide a significant portion of future U.S. and world electrical energy (Gregory et al., 1997). Photovoltaic cells produce electricity when sunlight excites electrons in the cells. The most promising photovoltaic cells in terms of cost, mass production, and relatively high efficiency are those manufactured using silicon. Because the size of the unit is flexible and adaptable, photovoltaic cells can be used in homes, industries, and utilities. However, photovoltaic cells need improvements to make them economically competitive before their use can become widespread. Test cells have reached efficiencies ranging from 20% to 25% (Sorensen, 2000), but the durability of photovoltaic cells must be lengthened and production costs reduced several times to make their use economically feasible.

Production of electricity from photovoltaic cells currently costs $0.12–$0.20 per kWh (DOE, 2000). Using massproduced photovoltaic cells with about 18% efficiency, 1 billion kWh/year of electricity could be produced on approximately 2800 ha of land, which is sufficient to supply the electrical energy needs of 100,000 people (Table 19.2; DOE, 2001). Locating the photovoltaic cells on the roofs of homes, industries, and other buildings would reduce the need for additional land by an estimated 20% and reduce transmission costs. However, because storage systems such as batteries cannot store energy for extended periods, photovoltaics require conventional backup systems.

The energy input for making the structural materials of a photovoltaic system capable of delivering 1 billion kWh during a life of 30 years is calculated to be approximately 143 million kWh. Thus, the energy input–output ratio for the modules is about 1:7 (Table 19.2; Knapp and Jester, 2000).

The major environmental problem associated with photovoltaic systems is the use of toxic chemicals, such as cadmium sulfide and gallium arsenide, in their manufacture (Bradley, 1997). Because these chemicals are highly toxic and persist in the environment for centuries, disposal and recycling of the materials in inoperative cells could become a major problem.

HYDROGEN AND FUEL CELLS

Using solar electric technologies for its production, gaseous hydrogen produced by the electrolysis of water has the potential to serve as a renewable fuel to power vehicles and generate electricity. In addition, hydrogen can be used as an energy storage system for various electric solar energy technologies (Winter and Nitsch, 1988; MacKenzie, 1994).

The material and energy inputs for a hydrogen production facility are primarily those needed to build and run a solar electric production facility, like photovoltaics and hydropower. The energy required to produce 1 billion kWh of hydrogen is 1.4 billion kWh of electricity (Ogden and Nitsch, 1993; Kreutz and Ogden, 2000). Photovoltaic cells (Table 19.2) currently require 2800 ha per 1 billion kWh; therefore, a total of 3920 ha would be needed to supply the equivalent of 1 billion kWh of hydrogen fuel. The water required for electrolytic production of 1 billion kWh per year equivalent of hydrogen is approximately 300 million L/year (Voigt, 1984). On a per capita basis, this amounts to 3000 L of water per year. The liquefaction of hydrogen requires significant energy inputs because the hydrogen must be cooled to about –253°C and pressurized. About 30% of the hydrogen energy is required for the liquefaction process (Peschka, 1992; Trainer, 1995).

Liquid hydrogen fuel occupies about three times the volume of an energy equivalent of gasoline. Storing 25 kg of gasoline requires a tank weighing 17 kg, whereas storing 9.5 kg of hydrogen requires a tank weighing 55 kg (Peschka, 1987, 1992). Although the hydrogen storage vessel is large, hydrogen burns 1.33 times more efficiently than gasoline in automobiles (Bockris and Wass, 1988). In tests, a Plymouth liquid hydrogen vehicle, with a tank weighing about 90 kg and 144 L of liquid hydrogen, has a cruising range in traffic of 480 km with a fuel efficiency of 3.3 km/L (MacKenzie, 1994). However, even taking into account its greater fuel efficiency, commercial hydrogen is more expensive at present than gasoline. About 3.7 kg of gasoline sells for about $1.20, whereas 1 kg of liquid hydrogen with the same energy equivalent sells for about $2.70 (Ecoglobe, 2001).

Fuel cells using hydrogen are an environmentally clean, quiet, and efficient method of generating electricity and heat from natural gas and other fuels. Fuel cells are electrochemical devices, much like storage batteries, that use energy from the chemical synthesis of water to produce electricity. The fuel cell provides a way to burn hydrogen using oxygen, capturing the electrical energy released (Larminie and Dicks, 2000). Stored hydrogen is fed into a fuel cell apparatus along with oxygen from the atmosphere, producing effective electrical energy (Larminie and Dicks, 2000). The conversion of hydrogen into direct current (DC) using a fuel cell is about 40% efficient.

The major costs of fuel cells are the electrolytes, catalysts, and storage. Phosphoric acid fuel cells (PAFCs) and proton exchange membrane fuel cells (PEMs) are the most widely used and most efficient. PAFCs have an efficiency of 40%–45%, compared to diesel engine efficiency of 36%–39%. However, PAFCs are complex and have high costs because they operate at temperatures of 50°C–100°C (DOE, 1999). A fuel cell PEM engine costs $500/kW, compared to $50/kW for a gasoline engine (DOE, 1999), leading to a total price of approximately $100,000 for an automobile running on fuel cells (Ogden and Nitsch, 1993). These prices are for specially built vehicles, and the costs should decline as they are massproduced. There is high demand for fuel cell-equipped vehicles in the United States (Larminie and Dicks, 2000).

Hydrogen has serious explosive risks because it is difficult to contain within steel tanks. Mixing with oxygen can result in intense flames because hydrogen burns more quickly than gasoline and diesel fuels (Peschka, 1992). Other environmental impacts are associated with the solar electric technologies used in hydrogen production. Water for the production of hydrogen may be a problem in arid regions of the United States and the world.

PASSIVE HEATING AND COOLING OF BUILDINGS

Approximately 20% (5.5 kWh × 1012 [19 quads]) of the fossil energy used each year in the United States is used for heating and cooling buildings and for heating hot water (USBC, 2001). At present only about 0.3 quads of energy are being saved by technologies that employ passive and active solar heating and cooling of buildings (Table 19.3), which means that the potential for energy savings through increased energy efficiency and through the use of solar technologies for buildings is tremendous. Estimates suggest that the amount of energy lost through poorly insulated windows and doors is approximately 1.1 × 1012 kWh (3.8 quads) each year—the approximate energy equivalent of all the oil pumped in Alaska per year (EETD, 2001).

Both new and established homes can be fitted with solar heating and cooling systems. Installing passive solar systems in new homes is less costly than retrofitting existing homes. Based on the cost of construction and the amount of energy saved, measured in terms of reduced heating and cooling costs over 10 years, the estimated returns of passive solar heating and cooling range from $0.02 to $0.10/kWh (Balcomb, 1992).

Improvements in passive solar technology are making it more effective and less expensive than in the past (Bilgen, 2000). Current research in window design focuses on the development of "superwindows" with high insulating values and "smart" or electrochromic windows that can respond to electric current, temperature, or sunlight to control the admission of light energy (Roos and Karlsson, 1994; DOE, 2000).

Although none of the passive heating and cooling technologies requires land, they are not without problems. Some indirect problems with land use may arise, concerning such issues as tree removal, shading, and rights to the sun (Simpson and McPherson, 1998). Glare from collectors and glazing may create hazards to automobile drivers and airline pilots. Also, when houses are designed to be extremely energy efficient and airtight, indoor air quality becomes a concern because of indoor air pollutants. However, well-designed ventilation systems with heat exchangers can take care of this problem.

GEOTHERMAL SYSTEMS

Geothermal energy uses natural heat present in Earth's interior. Examples are geysers and hot springs, like those at Yellowstone National Park in the United States. Geothermal energy sources are divided into three categories: hydrothermal, geopressured-geothermal, and hot dry rock. The hydrothermal system is the simplest and most commonly used one for electricity generation. The boiling liquid underground is utilized through wells, high internal pressure drives, or pumps.

In the United States, nearly 3000 MW of installed electric generation comes from hydrothermal resources, and this figure is projected to increase by 1500 MW within the next 20 years (DOE/EIA, 1991, 2001).

Most of the geothermal sites for electrical generation are located in California, Nevada, and Utah (DOE/EIA, 1991). Electrical generation costs for geothermal plants in the West range from $0.06 to $0.30 per kWh (Gawlik and Kutscher, 2000), suggesting that this technology offers potential to produce electricity economically. The U.S. Department of Energy and the Energy Information Administration (DOE/EIA, 1991, 2001) project that geothermal electric generation may grow three- to fourfold during the next 20–40 years. However, other investigations are not as optimistic and, in fact, suggest that geothermal energy systems are not renewable because the sources tend to decline over 40–100 years (Bradley, 1997; Youngquist, 1997; Cassedy, 2000). Existing drilling opportunities for geothermal resources are limited to a few sites in the United States and the world (Youngquist, 1997).

Potential environmental problems with geothermal energy include water shortages, air pollution, waste effluent disposal, subsidence, and noise (DOE/EIA, 1991). The wastes produced in the sludge include toxic metals such as arsenic, boron, lead, mercury, radon, and vanadium (DOE/EIA, 1991). Water shortages are an important limitation in some regions (OECD, 1998). Geothermal systems produce hydrogen sulfide, a potential air pollutant; however, this product could be processed and removed for use in industry (Bradley, 1997). Overall, the environmental costs of geothermal energy appear to be minimal relative to those of fossil fuel systems.

BIOGAS

Wet biomass materials can be converted effectively into usable energy with anaerobic microbes. In the United States, livestock dung is normally gravity fed or intermittently pumped through a plug-flow digester, which is a long, lined, insulated pit in the Earth. Bacteria break down volatile solids in the manure and convert them into methane gas (65%) and carbon dioxide (35%) (Pimentel, 2001). A flexible liner stretches over the pit and collects the biogas, inflating like a balloon. The biogas may be used to heat the digester, to heat farm buildings, or to produce electricity. A large facility capable of processing the dung from 500 cows costs nearly $300,000 (EPA, 2000).

The Environmental Protection Agency (EPA, 2000) estimates that more than 2000 digesters could be economically installed in the United States.

The amount of biogas produced is determined by the temperature of the system, the microbes present, the volatile solids content of the feedstock, and the retention time. A plug-flow digester with an average manure retention time of about 16 days under winter conditions (−17.4°C) produced 452,000 kcal/day and used 262,000 kcal/day to heat the digester to 35°C (Jewell et al., 1980). Using the same digester during summer conditions (15.6°C) but reducing the retention time to 10.4 days, the yield in biogas was 524,000 kcal/day, with 157,000 kcal/day used for heating the digester (Jewell et al., 1980). The energy input–output ratios for the digester in these winter and summer conditions were 1:1.7 and 1:3.3, respectively. The energy output of biogas digesters has changed little over the past two decades (Sommer and Husted, 1995; Hartman et al., 2000).

In developing countries such as India, biogas digesters typically treat the dung from 15 to 30 cattle from a single family or a small village. The resulting energy produced for cooking saves forests and preserves the nutrients in the dung. The capital cost for an Indian biogas unit ranges from $500 to $900 (Kishore, 1993). The price value of one kWh of biogas in India is about $0.06 (Dutta et al., 1997). The total cost of producing about 10 million kcal of biogas is estimated to be $321, assuming the cost of labor to be $7/h; hence, the biogas has a value of $356. Manure processed for biogas has little odor and retains its fertilizer value (Pimentel, 2001).

BIOFUELS: ETHANOL, METHANOL, AND VEGETABLE OIL

Petroleum, essential for the transportation sector and the chemical industry, makes up approximately 40% of total U.S. energy consumption. Clearly, as the supply diminishes, a shift from petroleum to alternative liquid fuels will be necessary. This analysis focuses on the potential of three fuel types: ethanol, methanol, and vegetable oil. Burned in internal combustion engines, these fuels release less carbon monoxide and sulfur dioxide than gasoline and diesel fuels; however, because the production of most of these biofuels requires more total fossil energy than they produce as a biofuel, they contribute to air pollution and global warming (Pimentel, 2001).

Ethanol production in the United States using corn is heavily subsidized by public tax money (Pimentel, 2001). However, numerous studies have concluded that ethanol production does not enhance energy security, is not a renewable energy source, is not an economical fuel, and does not ensure clean air. Furthermore, its production uses land suitable for crop production (Weisz and Marshall, 1980; Pimentel, 1991; Youngquist, 1997; Pimentel, 2001). Ethanol produced using sugarcane is more energy efficient than that produced using corn; however, more fossil energy is still required to produce a liter of ethanol than the energy output in ethanol (Pimentel et al., 1988).

The total energy input to produce 1000 L of ethanol in a large plant is 8.7 million kcal (Pimentel, 2001). However, 1000 L of ethanol has an energy value of only 5.1 million kcal and represents a net energy loss of 3.6 million kcal per 1000 L of ethanol produced. Put another way, about 70% more energy is required to produce ethanol than the energy that ethanol contains (Pimentel, 2001).

Methanol can be produced from a gasifier–pyrolysis reactor using biomass as a feedstock (Hos and Groenveld, 1987; Jenkins, 1999). The yield from 1 t of dry wood is about 370 L of methanol (Ellington et al., 1993; Osburn and Osburn, 2001). For a plant with economies of scale to operate efficiently, more than 1.5 million ha of sustainable forest would be required to supply it (Pimentel, 2001). Biomass is generally not available in such enormous quantities, even from extensive forests, at acceptable prices. Most methanol today is produced from natural gas.

Processed vegetable oils from sunflower, soybean, rape, and other oil plants can be used as fuel in diesel engines. Unfortunately, producing vegetable oils for use in diesel engines is costly in terms of both time and energy (Pimentel, 2001).

TRANSITION TO RENEWABLE ENERGY ALTERNATIVES

Despite the environmental and economic benefits of renewable energy, the transition to large-scale use of this energy presents some difficulties. Renewable energy technologies, all of which require land for collection and production, must compete with agriculture, forestry, and urbanization for land in the United States and the world. The United States already devotes as much prime cropland per capita to food production as is possible, given the size of the U.S. population, and the world has only half the cropland per capita that it needs for a diverse diet and an adequate supply of essential nutrients (USBC, 2001; USDA, 2001). In fact, more than 3 billion people are already malnourished in the world (WHO, 1996, 2000). According to some sources, the U.S. and world population could double in the next 50 and 70 years, respectively; all the available cropland and forest land would be required to provide vital food and forest products (PRB, 2001).

As the growing U.S. and world populations demand increased electricity and liquid fuels, constraints like land availability and high investment costs will restrict the potential development of renewable energy technologies. Energy use is projected on the basis of current growth to increase from the current consumption of nearly 100 quads to approximately 145 quads by 2050 (USBC, 2001). Land availability is also a problem, with the U.S. population increasing by about 3.3 million people each year (USBC, 2001). Each person added requires about 0.4 ha (1 acre) of land for urbanization and highways and about 0.5 ha of cropland (Vesterby and Krupa, 2001).

Renewable energy systems require more labor than fossil energy systems. For example, wood-fired steam plants require several times more workers than coal-fired plants (Pimentel et al., 1988; Giampietro et al., 1998).

An additional complication in the transition to renewable energies is the relationship between the location of ideal production sites and large population centers. Ideal locations for renewable energy technologies are often remote, such as the deserts of the American Southwest or wind farms located kilometers offshore. Although these sites provide the most efficient generation of energy, delivering this energy to consumers presents a logistical problem. For instance, networks of distribution cables must be installed, costing about $179,000/km of 115-kV lines (DOE/EIA, 2002). A percentage of the power delivered is lost as a function of electrical resistance in the distribution cable. There are five complex alternating current electrical networks in North America, and four of these are tied together by DC lines (Casazz, 1996).

Based on these networks, it is estimated that electricity can be transmitted up to 1500 km.

A sixfold increase in installed technologies would provide the United States with approximately 13.1 × 1012 (thermal) kWh (45 quads) of energy, less than half of current U.S. consumption (Table 19.1). This level of energy production would require about 159 million ha of land (17% of U.S. land area). This percentage is an estimate and could increase or decrease, depending on how the technologies evolve and energy conservation is encouraged.

Worldwide, approximately 408 quads of all types of energy are used by the population of more than 6 billion people (Table 19.1). Using available renewable energy technologies, an estimated 200 quads of renewable energy could be produced worldwide on about 20% of the land area of the world. A self-sustaining renewable energy system producing 200 quads of energy per year for about 2 billion people would provide each person with about 5000 L of oil equivalents per year—approximately half of America's current consumption per year, but an increase for most people of the world (Pimentel et al., 1999).

The first priority of the U.S. energy program should be for individuals, communities, and industries to conserve fossil fuel resources by using renewable resources and by reducing consumption. Other developed countries have proved that high productivity and a high standard of living can be achieved with the use of half the energy expenditure of the United States (Pimentel et al., 1999). In the United States, fossil energy subsidies of approximately $40 billion/year should be withdrawn and the savings invested in renewable energy research and education to encourage the development and implementation of renewable technologies. If the United States became a leader in the development of renewable energy technologies, then it would likely capture the world market for this industry (Shute, 2001).

CONCLUSION

This assessment of renewable energy technologies confirms that these techniques have the potential to provide the nation with alternatives to meet approximately half of future U.S. energy needs. To develop this potential, the United States would have to commit to the development and implementation of nonfossil fuel technologies and energy conservation. The implementation of renewable energy technologies would reduce many of the current environmental problems associated with fossil fuel production and use.

The immediate priority of the United States should be to speed the transition from reliance on nonrenewable fossil energy resources to reliance on renewable energy technologies. Various combinations of renewable technologies should be developed, consistent with the characteristics of the different geographic regions in the United States. A combination of the renewable technologies listed in Table 19.3 should provide the United States with an estimated 45 quads of renewable energy by 2050. These technologies should be able to provide this much energy without interfering with required food and forest production.

If the United States does not commit itself to the transition from fossil to renewable energy during the next decade or two, the economy and national security will be at risk. It is of paramount importance that U.S. residents work together to conserve energy, land, water, and biological resources. To ensure a reasonable standard of living in the future, there must be a fair balance between human population density and use of energy, land, water, and biological resources.

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REFERENCES

Alfheim, I. and T. Ramdahl. 1986. *Mutagenic and Carcinogenic Compounds from Energy Generation*. Oslo (Norway): Senter for Industriforkning.

American Petroleum Institute (API). 1999. *Basic Petroleum Data Book*. Washington, D.C.: API.

American Wind Energy Association (AWEA). 2000a. Wind energy and climate change (20 October 2002; www.awea.org/pubs/factsheets/climate.pdf).

American Wind Energy Association (AWEA). 2000b. Wind energy: The fuel of the future is ready today (20 October 2002; www.awea.org/pubs/factsheets/wetoday.pdf).

Baechler, M.C. and A.D. Lee. 1991. Implications of environmental externalities assessments for solar thermal power plants. In T.T. Mancini, K. Watanabe, and D.E. Klett (eds.), *Solar Engineering 1991*, pp. 151–158. New York: American Society of Mechanical Engineers.

Balcomb, J.D. 1992. Introduction. In J.D. Balcomb (ed.), *Passive Solar Buildings*, pp. 1–37. Cambridge, MA: Massachusetts Institute of Technology Press.

Bilgen, E. 2000. Passive solar massive wall systems with fins attached on the heated wall and without glazing. *Journal of Solar Energy Engineering* 122: 30–34.

Birdsey, R.A. 1992. *Carbon Storage and Accumulation in United States Forest Ecosystems*. Washington, D.C.: USDA Forest Service.

Bockris, J.O.M. and J.C. Wass. 1988. About the real economics of massive hydrogen production at 2010 AD. In T.N. Veziroglu and A.N. Protsenko (eds.), *Hydrogen Energy Progress,* pp. 101–151. VII. New York: Pergamon Press.

Bradley, R.L. 1997. *Renewable Energy: Not Cheap, Not "Green."* Washington, D.C.: Cato Institute.

British Petroleum (BP). 2001. *British Petroleum Statistical Review of World Energy*. London: British Petroleum Corporate Communications Services.

Brown, L.R. and P.B. Moyle. 1993. Distribution, ecology, and status of the fishes of the San Joaquin River drainage, California. *California Fish and Game* 79: 96–114.

Casazz, J.A. 1996. Transmission access and retail wheeling: The key questions. In M. Einhorn and R. Siddiqui (eds.), *Electricity Transmission Pricing and Technology*, pp. 77–102. Boston, MA: Kluwer Academic.

Cassedy, E.S. 2000. *Prospects for Sustainable Energy*. New York: Cambridge University Press.

Chambers, A. 2000. Wind power spins into contention. *Power Engineering* 104: 14–18.

Clarke, A. 1991. Wind energy progress and potential. *Energy Policy* 19: 742–755.

Dickson, Y.L. and B.C. Yates. 1983. *Examination of the Environmental Effects of Salt-Gradient Solar Ponds in the Red River Basin of Texas*. Denton, TX: North Texas State University.

DP Energy. 2002. Got wind? (October 20, 2002; www.dpenergy.com/page7.htm).

Duncan, R.C. 2001. World energy production, population growth, and the road to the Olduvai Gorge. *Population and Environment* 22: 503–522.

Dutta, S., I.H. Rehman, P. Malhortra, and R.P. Venkata. 1997. *Biogas: The Indian NGO Experience*. Delhi, India: Tata Energy Research Institute.

Ecoglobe. 2001. Hydrogen energy (November 6, 2002; www.ecoglobe.org.nz/energy/hydrogen.htm).

Ellington, R.T., M. Meo, and D.A. El-Sayed. The net greenhouse warming forcing of methanol produced from biomass. *Biomass and Bioenergy* 4: 405–418.

Environmental Energy Technologies Division–Lawrence Berkeley National Laboratory (EETD). 2001. Home energy saver (October 20, 2002; http://hes.lbl.gov).

Federal Energy Regulatory Commission (FERC). 1984. *Hydroelectric Power Resources of the United States*. Washington, D.C.: FERC.

Ferguson, A.R.B. 2001. *Biomass and Energy*. Manchester, UK: Optimum Population Trust.

Gaudiosi, G. 1996. Offshore wind energy in the world context. *Renewable Energy* 9: 899–904.

Gawlik, K. and C. Kutscher. 2000. *Investigation of the Opportunity for Small-Scale Geothermal Power Plants in the Western United States*. Golden, CO: National Renewable Energy Laboratory.

Giampietro, M., A. Ulgiati, and D. Pimentel. 1998. Feasibility of large-scale biofuel production. *BioScience* 47: 587–600.

Gleick, P.H. and A.D. Adams. 2000. *Water: The Potential Consequences of Climate Variability and Change*. Oakland, CA: Pacific Institute for Studies in Development, Environment, and Security.

Godish, T. 1991. *Air Quality*. Chelsea, MI: Lewis Publishers.

Gregory, J., S. Silviera, A. Derrick, P. Cowley, C. Allinson, and O. Paish. 1997. *Financing Renewable Energy Projects: A Guide for Development Workers*. London: Intermediate Technology Publications.

Hall, D.O. 1992. *Biomass*. Washington, D.C.: World Bank.

Hartman, H., I. Angelidake, and B.K. Ahring. 2000. Increase of anaerobic degradation of particulate organic matter in full-scale biogas plants by mechanical maceration. *Water Science and Technology* 41: 145–153.

Hos, J.J. and M.J. Groenveld. 1987. Biomass gasification. In D.O. Hall and R.P. Overend (eds.), *Biomass*, pp. 237–255. Chichester, UK: John Wiley & Sons.

Hull, J.R. 1986. Solar ponds using ammonium salts. *Solar Energy* 36: 551–558.

International Commission on Large Dams (ICLD). 1988. *World Register of Dams*. Paris: ICLD.

International Energy Agency (IEA). 1987. *Renewable Sources of Energy*. Paris: IEA.

Jenkins, B.M. 1999. Pyrolysis gas. In O. Kitani, T. Jungbluth, R.M. Peart, A. Ramdani (eds.), *CIGAR Handbook of Agricultural Engineering*, pp. 222–248. St. Joseph, MI: American Society of Agricultural Engineering.

Jewell, W.J., S. Dell'orto, K.J. Fanfoli, T.D. Hates, A.P. Leuschner, D.F. Sherman. 1980. *Anaerobic Fermentation of Agricultural Residue: Potential for Improvement and Implementation*. Washington, D.C.: U.S. Department of Energy.

Kellet, J. 1990. The environmental impacts of wind energy developments. *Town Planning Review* 91: 139–154.

Kerlinger, P. 2000. *Avian Mortality and Communication Towers: A Review of Recent Literature, Research, and Methodology*. Washington, D.C.: U.S. Fish and Wildlife Service, Office of Migratory Bird Management.

Kishore, V.V.N. 1993. Economics of solar pond generation. In V.V.N. Kishore (ed.), *Renewable Energy Utilization: Scope, Economics, and Perspectives*, pp. 53–68. New Delhi, India: Tata Energy Research Institute.

Kitani, O. 1999. Biomass resources. In O. Kitani, T. Jungbluth, R.M. Peart, and A. Ramdami (eds.), *Energy and Biomass Engineering*, pp. 6–11. St. Joseph, MI: American Society of Agricultural Engineers.

Knapp, K.E. and T.L. Jester. 2000. An empirical perspective on the energy payback time for photovoltaic modules. American Solar Energy Society Solar 2000 Conference; June 16–21, 2000; Madison, WI (November 8, 2002; www.ecotopia.com/apollo2/knapp/pvepbtpaper.pdf).

Kreutz, T.G. and J.M Ogden. 2000. Assessment of hydrogen-fueled proton exchange membrane fuel cells for distributed generation and cogeneration. *Proceedings of the 2000 U.S. Department of Energy Hydrogen Program Review; Washington, D.C.* NREL/CP-570-28890.

Larminie, J. and A. Dicks. 2000. *Fuel Cell Systems Explained*. Chichester, UK: John Wiley & Sons.

Ligon, F.K., W.E. Dietrich, and W.J. Trush. 1995. Downstream ecological effects of dams: A geomorphic perspective. *BioScience* 45: 183–192.

MacKenzie, J.J. 1994. *The Keys to the Car: Electric and Hydrogen Vehicles for the 21st Century*. Washington, D.C.: World Resources Institute.

Natural Resources Canada (NRC). 2002. Technologies and applications (October 20, 2002; www.canren.gc.ca/tech_appl/index.asp?Cald=6&Pgld=232).

Nelson, V. 1996. *Wind Energy and Wind Turbines*. Canyon, TX: Alternative Energy Institute.

Nilsson, C. and K. Berggren. 2000. Alterations of riparian ecosystems caused by river regulation. *BioScience* 50: 783–792.

Ogden, J.M. and J. Nitsch. 1993. Solar hydrogen. In T.B. Johansson, H. Kelly, A.K.N. Reddy, and R.H. Williams (eds.), *Renewable Energy: Sources for Fuels and Electricity*, pp. 925–1010. Washington, D.C.: Island Press.

Organisation for Economic Co-operation and Development (OECD). 1998. *Environmental Impacts of Renewable Energy*. Paris: OECD.

Osburn, L. and J. Osburn. 2001. Biomass resources for energy and industry (October 20, 2002; www.ratical.com/renewables/biomass.html).

Peschka, W. 1987. The status of handling and storage techniques for liquid hydrogen in motor vehicles. *International Journal of Hydrogen Energy* 12: 753–764.

Peschka, W. 1992. *Liquid Hydrogen: Fuel of the Future*. New York: Springer Verlag.

Pimentel, D. 1991. Ethanol fuels: Energy security, economics, and the environment. *Journal of Agricultural and Environmental Ethics* 4: 1–13.

Pimentel, D. 2001. The limitations of biomass energy. In *Encyclopedia of Physical Sciences and Technology*, pp. 159–171. San Diego, CA: Academic Press.

Pimentel, D., A.F. Warneke, W.S. Teel, K.A. Schwab, N.J. Simcox, D.M. Evert, K.D. Baenisch, and M.R. Aaron. 1988. Food versus biomass fuel: Socioeconomic and environmental impacts in the United States, Brazil, India, and Kenya. *Advanced Food Research* 32: 185–238.

Pimentel, D. et al. 1994. Renewable energy: Economic and environmental issues. *BioScience* 44: 536–547.

Pimentel, D., O. Bailey, P. Kim, E. Mullaney, J. Calabrese, F. Walman, F. Nelson, and X. Yao. 1999. Will the limits of the Earth's resources control human populations? *Environment, Development and Sustainability* 1: 19–39.

Population Reference Bureau (PRB). 2001. *World Population Data Sheet*. Washington, D.C.: PRB.

Reddy, A.K.N., R.H. Williams, and T.B. Johansson. 1997. *Energy after Rio: Prospects and Challenges*. New York: United Nations Development Programme.

Repetto, R. 1992. Accounting for environmental assets. *Scientific American* 263: 94–100.

Roos, A. and B. Karlsson. 1994. Optical and thermal characterization of multiple glazed windows with low U-values. *Solar Energy* 52: 315–325.

Schneider, S.H., W.E. Easterling, and L.O. Mearms. 2000. Adaptation: Sensitivity to natural variability, agent assumptions, and dynamic climatic changes. *Climatic Change* 45: 203–221.

Schumer, C.E. 2001. New Analysis Shows America on Precipice of an Energy Crunch. Press Release of Senator Charles E. Schumer. April 26, 2001.

Shute, N. 2001. The weather: Global warming could cause droughts, disease, and political upheaval. *U.S. News & World Report*, November 11, 2001, pp. 44–52.

Simpson, J.R. and E.G. McPherson. 1998. Simulation of tree shade impacts on residential energy use for space conditioning in Sacramento. *Atmospheric Environment* 32: 69–74.

Smil, V. 1994. *Energy in World History*. Boulder, CO: Westview Press.

Smith, D.R. and M.A. Ilyin. 1991. Wind and solar energy: Costs and value. In D.E. Berg and P.S. Veers (eds.), *The American Society of Mechanical Engineers 10th Annual Wind Energy Symposium*, pp. 29–32. January 20–23, 1991; Houston, TX.

Sommer, S.G. and S. Husted. 1995. The chemical buffer system in raw and digested animal slurry. *Journal of Agricultural Science* 124: 45–53.

Sorensen, B. 2000. *Renewable Energy: Its Physics, Engineering, Use, Environmental Impact, Economics, and Planning Aspects*. San Diego, CA: Academic Press.

Tabor, H.Z. and B. Doran. 1990. The Beith Ha'arva 5MW (e) solar pond power plant (SPPP): Progress report. *Solar Energy* 45: 247–253.

Trainer, F.E. 1995. Can renewable energy sources sustain affluent society? *Energy Policy* 23: 1009–1026.

U.S. Bureau of the Census (USBC). 2001. *Statistical Abstract of the United States 1999*. Washington, D.C.: USBC.

U.S. Department of Agriculture (USDA). 2001. *Agricultural Statistics*. Washington, D.C.: USDA.

U.S. Department of Energy (DOE). 1999. *Fuel Cells for the 21st Century: Collaboration for a Leap in Efficiency and Cost Reduction*. Washington, D.C.: DOE.

U.S. Department of Energy (DOE). 2000. Consumer energy information: EREC fact sheets (October 20, 2002; www.eren.doe.gov/erec/factsheets/eewindows.html).

U.S. Department of Energy (DOE). 2001. Energy efficiency and renewable energy network (January 16, 2001; www.eren.doe.gov/state_energy/tech_solar.cfm?state=NY).

U.S. Department of Energy–Energy Information Administration (DOE/EIA). 1991. *Geothermal Energy in Western United States and Hawaii: Resources and Projected Electricity Generation Supplies*. Washington, D.C.: DOE/EIA.

U.S. Department of Energy–Energy Information Administration (DOE/EIA). 2001. *Annual Energy Outlook with Projections to 2020*. Washington, D.C.: DOE/EIA.

U.S. Department of Energy–Energy Information Administration (DOE/EIA). 2002. *Annual Energy Outlook with Projections to 2020*. Washington, D.C.: DOE/EIA.

U.S. Department of Energy–Energy Efficiency and Renewable Energy Network (DOE/EREN). 2001. Solar parabolic troughs: Concentrating solar power (February 28, 2001; www.eren.doe.gov/csp/faqs.html).

U.S. Environmental Protection Agency (EPA). 2000. *AgSTAR Digest.* Washington, D.C.: EPA.

U.S. Environmental Protection Agency (EPA). 2002. Wood smoke (October 20, 2002; http://216.239.51.100/search?q=cache:bnh0QlyPH20C:www.webcom.com/~bi/brochure.pdf+wood+smoke+pollution&hl=en&ie=UTF-8).

Vesterby, M. and S. Krupa. 2001. Major Uses of Land in the United States, 1997. Washington, D.C.: Resource Economics Division, Economic Research Service, USDA. Statistical Bulletin No. 973 (October 20, 2002; www.ers.usda.gov/publications/sb973/).

Voigt, C. 1984. Material and energy requirements of solar hydrogen plants. *International Journal of Hydrogen Energy* 9: 491–500.

Weisz, P.B. and J.F. Marshall. 1980. *Fuels from Biomass: A Critical Analysis of Technology and Economics.* New York: Marcel Dekker.

Winter, C.J. and J. Nitsch. 1988. *Hydrogen as an Energy Carrier: Technologies, Systems, and Economy.* Berlin: Springer-Verlag.

Winter, C.J., Meineke, W., and A. Neumann. 1991. Solar thermal power plants: No need for energy raw material—only conversion technologies pose environmental questions. In M.E. Arden, S.M.A. Burley, and M. Coleman (eds.), *1991 Solar World Congress*, pp. 1981–1986. Oxford, UK: Pergamon Press.

World Bank. 1992. *China: Long-Term Issues and Options in the Health Transition.* Washington, D.C.: World Bank.

World Health Organization (WHO). 1996. Micronutrient Malnutrition: Half of the World's Population Affected. Geneva, Switzerland: WHO. Press release.

World Health Organization (WHO). 2000. Malnutrition worldwide (October 20, 2002; www.who.int/nut/malnutrition_worldwide.htm).

World Health Organization–United Nations Environment Programme (WHO/UNEP). 1993. Urban Air Pollution in Megacities of the World. Geneva, Switzerland: WHO/UNEP.

Youngquist, W. 1997. *GeoDestinies: The Inevitable Control of Earth Resources over Nations and Individuals.* Portland, OR: National Book Company.

20 Biomass: Food versus Fuel

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Biomass resources (fuelwood, dung, crop residues, ethanol) constitute a major fuel source in the world (Hall et al., 1985; Pimentel et al., 1986a; Hall and de Groot, 1987). Biomass is a prime energy source in developing nations, where it meets about 90% of the energy needs of the poor (Chatterji, 1981). Each year 2.5 billion tons of forest resources are harvested for a variety of uses, including fuel, lumber, and pulp (FAO, 1983a). About 60% of these resources are harvested in developing nations; of this amount, about 85% is burned as fuel (Montalembert and Clement, 1983). Fuelwood makes up about half (1.3 billion tons) of the 2.8 billion tons of biomass consumed annually worldwide; the remaining half consists of crop residues (33%) and dung (17%) (Pimentel et al., 1986b).

High fossil fuel prices and rapid population growth in developing countries have made it necessary for the people there to rely more on biomass in the form of fuelwood, crop residues, and dung for energy (Dunkerley and Ramsay, 1983; OTA, 1984; Sanchez-Sierra and Umana-Quesada, 1984). Estimates are that the poor in developing nations spend 15%–40% of their income for fuel and devote considerable time and energy to collecting biomass for fuel (CSE, 1982; Hall, 1985).

BIOMASS RESOURCES

The use of biomass for food and energy in the United States, Brazil, India, and Kenya is compared here. These countries were selected because they represent different economic, social, and environmental conditions.

UNITED STATES

The United States, with 917 million ha of land and a human population of 256 million (Table 20.1), is the largest of the four countries in land area and the second largest in total population. It has the lowest rate of population growth but the largest per capita GNP (gross national product) (Table 20.1).

Nearly half of the land area in the United States is used for crop production and pastures (Table 20.2). The extensive forested area of 290 million ha provides only about 4% of the total energy used in the United States (Tables 20.2 and 20.3). Fossil fuel resources are the major sources of U.S. energy. In per capita use of biomass for fuel, the United States ranks third—just ahead of India (Table 20.2).

TABLE 20.1
Population, Area, and per Capita Gross National Product (GNP)

Country	Estimated Population (10^6)[a]	Annual Rate of Increase (%)	Surface Area (10^6 km^2)[a]	Density (Habitants/km^2)	GNP ($ per Capita)
United States	256	1.1[b]	9.17	28	22,560
Brazil	152	1.5[c]	8.51	18	2920
India	897	2.1[c]	3.28	273	330
Kenya	28	3.7[c]	0.58	48	340

[a] UN (1976).

[b] USBC (1992).

[c] PRB (1993).

TABLE 20.2
Land Distribution by Uses and Population Engaged in Agriculture[a]

Country	Total Area (10^6 ha)	Cropland (10^6 ha)	Pasture (10^6 ha)	Forests and Woods (10^6 ha)	Other land (10^6 ha)	Percentage of Laborers in Agriculture
United States[a,b]	917	192	300	290	135	4
Brazil[a,c]	845	60	184	493	108	31
India[a,c]	298	170	12	67	49	70
Kenya[a,c]	57	2.4	38	2.3	14	81

[a] WRI (1992).

[b] USDA (1991a).

[c] WRI (1984).

TABLE 20.3
Consumption of Commercial Energy (10^{12} kcal)

Country	Solid Fuels[a]	Liquid Fuels[a]	Natural Gas[a]	Hydroelectric and Nuclear[a]	Total	Per Capita (10^6 kcal)
United States[a]	4300	7775	4475	1825	18,375	76.6
Brazil[b]	57	383	19	132	591	4.1
India[b]	439	295	18	104	856	1.1
Kenya	0.8	9.9	0	1.6	12.3	0.6

[a] DOE (1983).

[b] UN (1986).

TABLE 20.4
Tons (10^6 Dry) of Biomass Energy Currently Used[a]

Country	Firewood	Animal Wastes	Bagasse and Crop Residues	Food Grains, Sugars, etc.	Total Biomass	Metric Tons per Capita of Biomass
United States[b]	166 (747)	1	4[c]	1	172	0.72
		(5)	(18)	(5)	(774)	
Brazil	102[d] (459)	Negligible	46[e]	10[e]	158	1.1
			(207)	(45)	(711)	
India	124[f] (558)	38[g]	64[g]	>0	226[f]	0.29
		(118)	(126)		(855)	
Kenya	20.4[e] (92)	11[e]	1.5[e]	>0	32.9[e]	1.57
		(50)	(7)		(148)	

[a] Values in parentheses indicate energy equivalent if dry biomass were incinerated (10^{12} kcal).

[b] ERAB (1981).

[c] Mostly sugarcane bagasse.

[d] UN (1982).

[e] Meade and Chen (1977); FAO (1984).

[f] UN (1982).

[g] Derived from Gl (1979).

Wood accounts for about 97% of the biomass used as fuel (Tables 20.3 through 20.7). The second largest quantity of biomass energy comes from bagasse, the byproduct of sugar production. About 172 million tons of biomass are converted for energy use each year, and this quantity could more than double, to about 440 million tons (ERAB, 1981; Pimentel et al., 1994). An increase of this magnitude would conflict with agricultural land needs and probably be detrimental to the environment.

BRAZIL

Brazil is the fifth largest country in the world, with 851 million ha of land. Its population of 152 million is increasing at a rate of 1.5% per year (Table 20.1), and its per capita GNP is $2920. At present, 45% of its total energy supply comes from fossil fuel and 55% from biomass fuel (Tables 20.3 and 20.4). Brazil's total annual biomass production is slightly less than that of the United States and more than that of India and Kenya (Table 20.5). Approximately 23% of the biomass produced in Brazil is used for food and fiber (Table 20.6).

Although forests still cover 67% of the country (Table 20.2), rapid deforestation is taking place, primarily caused by slash and burn agriculture rather than by commercial logging or cattle production (Myers, 1986a). Much of the tropical rainforest has limited potential as fuel resource because it is located in remote areas and far from consumers. Firewood provides 22% of the country's total energy needs (Tables 20.3 and 20.4). Forests not only are important to Brazil as an energy source but also, as in all areas, protect land from soil erosion, reduce flooding, and minimize the silting of river streams, and human-made reservoirs.

TABLE 20.5
Annual Biomass Production in the United States, Brazil, India, and Kenya[a]

	United States		Brazil		India		Kenya	
	Land Area (10^6 ha)	Biomass Production	Land Area (10^6 ha)	Biomass Production	Land Area (10^6 ha)	Biomass Production	Land Area (10^6 ha)	Biomass Production
Arable land and production crops	192	1083	75	450	143	858	2.3	13.8
Pasture and grazing land	300	900	164	492	12	36	6.2	18.6
Forests	290	580	568	1136	46	92	2.4	94.8
Other	135	68	39	20	127	64	46.1	50.7[b]
Total area	917	—	851	—	328	—	57	—
Total biomass	—	2631	—	2098	—	1050	—	84.2
Total energy fixed (10^{15} kcal)	11.8		9.4		4.7		0.38	
Solar fixed energy per capita (10^6 kcal)	59.2		104		6.0		18.1	
Biomass production (t/ha)	2.9		2.5		3.2		1.5	

[a] The average biomass yields per hectare were crops, 6 t; pastures, 3 t; forests, 2 t; and other, 0.5 t.

[b] Calculated using figures for woody biomass production given by O'Keefe et al. (1984) and assuming an annual nonwoody biomass production of 1 t/ha in arid grasslands.

TABLE 20.6
Total Annual Amount of Solar Energy Harvested in the Form of Agricultural Crops and Forestry Products (Dry)

	United States		Brazil		India		Kenya	
	10^6 metric tons[a]	10^{12} kcal	10^6 metric tons[a]	10^{12} kcal	10^6 metric tons[a]	10^{12} kcal	10^6 metric tons[a]	10^{12} kcal
Corn	194	873	21	95	7.8	35	1.3	6
Wheat	71	320	1.8	8	45	203	0.1	0.5
Rice	6	27	9	41	91	410	0.03	0.1
Soybeans	51	230	16	72	8	4	—	—
Sorghum	22	99	0.3	14	12	54	0.15	0.7
Potatoes	16	72	0.4	18	2.4	11	0.1	0.5
Cassava	—	—	4.2	19	1.2	5	0.15	0.7
Vegetables	6	27	1.8	8	8.8	40	0.02	0.5
Fruits	5	23	4.9	22	3.9	18	0.15	0.7
Nuts	0.8	4	0.1	0.5	0.2	0.9	0.02	0.1
Oil seeds	9	41	2.0	9	18	365	0.13	0.6
Sugarcane	2.5	—	24.1	105	18	81	0.4	1.8
Sugar beets	2	27	—	—	—	—	—	—
Pulses	1	5	2.7	24	13	59	0.25	1.1
Oats	7	32	0.1	0.5	—	—	0.01	0.05
Rye	1	5	<0.1	<0.5	—	—	—	—
Barley	13	59	0.1	0.5	—	—	0.09	0.4
Subtotal	407.3	1833	88.6	399	229.3	1032	2.9	13.1
Pasture and others	900[b]	4050	492[b]	2214	36[b]	162	19[b]	85
Forest industrial products	100[c]	450	40[d]	180	14[d]	63	0.8[e]	2.3
Total	1407	6332	7590	2655	274	1235	22.4	101
Total per capita (tons)	5.8		4.1		0.3		1.1	
Total per capita (10^6 kcal)	26.3		18.6		1.6		4.8	

[a] From data presented by the Food and Agriculture Organization (FAO, 1984).

[b] From Table 20.5.

[c] USDA (1985).

[d] FAO (1983b).

[e] O'Keefe and Raskin (1985).

After the 1973 oil crisis, Brazil embarked on an ambitious plan to produce ethanol from sugarcane in an effort to reduce its dependence on foreign oil. Currently, Brazil has the largest ethanol system in the world, producing 12 billion L annually, primarily from sugarcane (Boddey, 1995). The United States produces only 2.4 billion L of ethanol annually, primarily from corn grain (DOE, personal communication, Information Office, Alcohol Fuels Program, Department of Energy, Washington, D.C., 1986). Ethanol supplies approximately 19% of Brazil's current biomass energy. However, expansion of the sugarcane crop for ethanol production

TABLE 20.7
Forest Utilization (10^6 t)

	Potential Sustainable Production[a]	Actual Use		
		Industry	Firewood	Total
United States	580	191[b]	166[c]	357
Brazil	1136	40[d]	102[e]	142
India	92	14[d]	124[f]	138
Kenya	2.5	0.8[g]	19.6[g]	20.4[c]

[a] Assuming a net productivity of 2 t/ha.
[b] USDA (1985).
[c] ERAB (1981).
[d] FAO (1983b).
[e] Bogach (1985).
[f] See Table 20.4.
[g] O'Keefe and Raskin (1985).

is associated with a decrease in the per capita production of domestic food crops. From 1974 to 1984 food production decreased 1.9% per year, whereas sugarcane production increased 7.8% per year (de Melo, 1986). The increasing demand for firewood, construction lumber, and sugarcane, combined with the effects of slash-and-burn agriculture, seem likely to continue to exacerbate problems in agricultural production and the quality of the environment.

INDIA

India's surface area is 36% that of the United States, but its population, at 897 million, is more than three times greater (Table 20.1). Of the four countries, India has the highest population density and the lowest GNP (Table 20.1). India's population growth rate remains at 1.7%, and country has more than 1.1 billion (PRB, 2006). A majority of the people live in rural areas and engage in agriculture.

Although India will have to increase food production to keep pace with population growth, it can expand its cropland only by removing forests (Mishra, 1986; Sharma, 1987). The present Indian forest area of about 67 million ha makes up only 23% of the country's total land area (Table 20.2). India is losing about 3.4 million ha of forestland each year (World Development Report, 1995), and there is virtually no forest growth left below 2000 m (Myers, 1986b). The principal factor responsible for this deforestation is population pressure imposed by both humans and livestock (Sharma, 1987). Most of India's large livestock population must graze on fallow agricultural land, uncultivated lands, and forest areas because little fodder is produced.

In addition to using biomass resources for food production, India relies heavily on biomass for energy. Biomass resources supply about half of the energy consumed, fossil energy the other half. The Indian household sector utilizes nearly all of the biomass energy consumed (Tables 20.3 and 20.4), primarily for cooking and lighting (Government of India, 1979). The sugar industry uses bagasse to provide heat and steam energy for the manufacture of sugar.

Wood is the primary source of biomass energy, making up 55% of all biomass energy consumed, followed by bagasse and crop residues at 28% and animal dung at 17% (Table 20.4). This pattern of biomass energy use in India resembles the world pattern, which averages about 50% wood, 35% crop residues, and 15% dung. However, India's heavy reliance on firewood is alarming because 45% more firewood is being used than its forest area can sustainably provide (Tables 20.5–20.7). It should be noted, however, that not all firewood in India is obtained from forests. Although in total forests are the greatest source of fuelwood (Government of India, 1979), about 22% of fuelwood is collected from nonforest land, such as privately owned plantations and woodlots, other private property, riverbanks, canals, and roadsides (Government of India, 1979). To meet future food and fuel needs, India will have to utilize more of its biomass resources; however, it is dubious if the land resources can sustain such use. Of the total annual biomass currently produced, India already harvests 25% in the form of fuel (Tables 20.4 and 20.5).

KENYA

Kenya occupies 570,000 km^2 of arid East Africa and has a population of 28 million people that is expanding at a rate of about 3.7% per annum (Table 20.1). The per capita GNP in Kenya is $340 (Table 20.1). Of the total land area, 4% is in forests and woodland, 4% is used for growing crops, and 7% is pastureland (Table 20.2). Parks and reserves occupy 4%–5%, and villages and cities occupy 1%. The remaining 80% of the land comprises semiarid savanna and rangeland.

Although 75% of the population lives on 20% of the land resulting in densities of 500–1000 people per km^2 (World Development Report, 1995), only 15% live in urban areas. In rural areas, 75% of the labor force is engaged in agriculture (Table 20.1). Per capita food production and caloric intake decreased during the 1970s. Thus, the daily per capita food supply was only 90% of the minimum requirement of 2340 kcal/person/day necessary for the maintenance of health (Yeager and Miller, 1986). In 1992–1993, Kenya imported 569,000 t of cereals and received another 287,000 t in aid.

Biomass provides the bulk of Kenya's energy needs (Tables 20.3 and 20.4), with firewood supplying 80% of the total annual energy requirements (F. Mugo, Nairobi, Kenya, personal communication, 1995). Most of the wood consumed (about 20 million tons) was removed from arable cropland, grazing land, and urbanlands. Only 27% came from forests, yet this amount still exceeded the sustainable yield of the forests by more than 50% (O'Keefe and Raskin, 1985). Consumption exceeded yields by 9 million tons, causing depletion of the standing stocks. The yearly rate of deforestation is 1.6%, primarily because of expanding agriculture but also because of increased needs for firewood (Molofsky et al., 1986).

In addition to wood, crop residues and dung are used to produce biomass energy. Crop residues, including bagasse, total about 4.2 million tons per year (Table 20.4). All bagasse is used in the sugar-refining process. Of the other crop residues, about 30%

of the total harvested biomass, including the woody residue from coffee and tea plantations, is used for energy (O'Keefe, 1983).

Of the 12 million tons of dung produced annually in Kenya, an estimated 0.6 million tons are burned. A survey by Hosier (1985) found that rural people burn animal dung when firewood supplies are insufficient, and then only for heating, not for cooking.

Ethanol production using molasses was started at Muhoroni, Kenya (Stuckey and Juma, 1985). (Another plant near Kisumu was discontinued after cost overruns had nearly tripled its initial $60 million cost.) The Muhoroni plant, which has a capacity to produce 64,000 L of ethanol per day, can produce 1 L of ethanol for $0.57, including the cost of molasses, running costs, capital costs, and transportation.

Of the total annual biomass production of 91.3 million tons in Kenya, only 35.2 million tons are produced on arable land, pastureland, and forests, where 80% of the population lives (Tables 20.4 and 20.5). Of these 35.2 t, about 54% is used for fuel and 8.2% for food (Banwell and Harriss, 1992). Further expansion of Kenyan agriculture and increased consumption of firewood will be necessary through 2000 and thereafter to support Kenya's rapidly growing population.

BIOMASS ENERGY USE

Forest and other biomass are produced from solar energy if temperature, soil, water, and biological resources are sufficient for plant growth. In the United States, 14.2×10^{15} kcal of solar energy is collected as plant biomass each year (Tables 20.5 through 20.7). This amounts to 3.0 t/ha/year (Table 20.5). The average yields for Brazil are 2.5 t/ha, for India 3.2 t/ha, and for Kenya 1.25 t/ha. The low yield for Kenya is due to low rainfall (Tables 20.5–20.7).

How does the amount of solar energy collected annually in biomass compare with fossil energy consumed? The United States uses about 40% more fossil energy than all the plant biomass in the United States captures in solar energy. In India, the fossil energy consumed represents about 18.2% of the total solar energy captured by plant biomass; in Brazil this percentage is 6.3%, and in Kenya only 3.5% (derived from Tables 20.3 and 20.5).

CONVERSION OF BIOMASS TO ETHANOL, BIOGAS, AND HEAT

The utilization of some forms of biomass for fuel requires conversion, which frequently requires significant inputs of energy and may cause environmental as well as social problems. In the following discussion, energy inputs, environmental impacts, and social costs are assessed for ethanol, biogas, and heat energy.

ETHANOL

The conversion of sugars to ethanol by fermentation is a well-established technology. Yeast carry out the fermentation in an 8- to 12-h batch process that produces 8%–10% ethanol by volume. The ethanol is then recovered by continuous distillation. Theoretically, each 1 g of sugar or starch should produce 0.51–0.57 g of ethanol. In practice, about 90% of the theoretical yields are achieved (the yeast population consumes

TABLE 20.8
Inputs per 1000 L of Ethanol from U.S. Sugarcane[a]

Inputs	kg	kcal × 10^3	Dollars
Sugarcane	14,000	1938[b]	167[b]
Transport of sugarcane	14,000	400[c]	42
Water	125,000[d]	70	20
Stainless steel	3[d]	45	10
Steel	4[d]	46	10
Cement	8[d]	15	5
Bagasse	1900	7600	—
Pollution costs	—	—	60
Total		10,114	314

[a] Outputs: 1000 L of ethanol = 5,130,000 kcal.

[b] Table 20.9.

[c] Estimated.

[d] Slesser and Lewis (1979).

some of the sugar and starch for its maintenance and growth). The yield of ethanol is about 1 L per 2.7 kg of corn or 14 kg of sugarcane (2.5 kg of sugar) (Table 20.8).

Sugarcane production in the United States requires significant dollar and fossil energy inputs (Table 20.9), which represent the major costs in ethanol production. (For details for producing ethanol from U.S. corn, see Chapter 19.) A hectare of U.S. sugarcane yields an average of 88,000 kg and requires 12.2 million kcal of fossil energy and $1059 to produce (Table 20.9).

Once the sugarcane is harvested, three additional energy costs are involved in its conversion to ethanol: transport to the plant, the conversion process, and pollution control. These costs in both energy and dollar terms are large for a modern chemical plant with an output of 200 million L per year (Pimentel, 1991).

Although the costs of producing ethanol are slightly lower for sugarcane than for corn ($0.31/L, see Chapter 19), the energetics are similar (Table 20.8). The total energy input to produce 1000 L of ethanol using sugarcane is 10.1 million kcal, or about double the energy value of the ethanol itself (5.1 million kcal). However, the fermentation/distillation process for ethanol produced from sugarcane has no energy cost because all the required energy is supplied by conversion of the bagasse by-product. However, in this assessment the fuel energy from the bagasse is charged as a cost (Table 20.8) because the bagasse could be used as an organic fertilizer or a fuel source for other processes. For the sugarcane system, sugarcane feedstock represents 53% of the cost of producing ethanol; thus, the price of the end product depends on the agricultural production costs.

Production of ethanol in the chemical plant also has major pollution costs (Table 20.8), which add 10%–15% to the overall cost of production. For each 1000 L of ethanol produced using sugarcane, 160,000 L of wastewater are produced. This wastewater has a biological oxygen demand (BOD) of 18,000–37,000 mg/L

TABLE 20.9
Average Energy Input and Output per Hectare per Year for Sugarcane in Louisiana[a,b]

	Quantity/ha	10^3 kcal/ha	Dollars/ha
Inputs			
Labor	30 h	21	150
Machinery	72 kg	1944	119
Gasoline	54 L	546	15
Diesel	284 L	3242	75
Nitrogen (ammonia)	158 kg	3318	84
Phosphorus (triple)	97 kg	611	49
Potassium (muriate)	149 kg	373	40
Lime	1120 kg	353	168
Seed	215 kg	802	215
Insecticide	2.5 kg	250	25
Herbicide	6.2 kg	620	62
Transportation	568.9 kg	146	57
Total		12,226	1059
Outputs			
Sugarcane	88,000 kg	24,618,000	
Sugar yield	6600 kg		

[a] Ricaud (1980).

[b] kcal input/kcal sugar = 2.01.

depending on the type of plant (Kuby et al., 1984). (The third supplemental energy input, transportation, is not included in this analysis.)

The foregoing data were based on U.S. sugarcane. Overall costs are slightly lower in Brazil than in the United States (Tables 20.8 and 20.10). The energy inputs for sugarcane production in Brazil are similar to those in the United States (Tables 20.9 and 20.11).

About 1.9 million kcal is required to produce 14,000 kg of sugarcane feedstock, which in turn produces 1000 L of Brazilian ethanol. These figures are similar to the energy inputs required in the United States (Tables 20.8 and 20.10). The total input to produce 1000 L of ethanol is about 9.9 million kcal, nearly double the yield in ethanol of 5.1 million kcal. About half a liter of imported fossil petroleum equivalent is needed to produce 1 L of ethanol (Table 20.10). Others have reported that it takes about 1 L of imported petroleum to produce 1 L of ethanol (Chapman, 1983; Chapman and Barker, 1987).

Brazilian ethanol costs \$0.30/L to produce (Table 20.10). This figure includes pollution costs of \$0.06/L. With the pollution costs removed, the cost is lowered to \$0.24/L, well within the range of \$0.23–\$0.27 reported by others (MME, 1987; Goldemberg, J. personal communication, Institute of Physics, University of São Paulo, Brazil, 1987). This \$0.30/L estimate does not factor in the crop subsidy; doing

TABLE 20.10
Inputs per 1000 L of Ethanol from Brazilian Sugarcane[a]

Inputs	kg	10^3 kcal	Dollars
Sugarcane	14,000	1946[b]	172[b]
Transport of sugarcane	14,000	195	24
Water	125,000	70[c]	20
Stainless steel	3	45[c]	10
Steel	4	46[c]	10
Concrete	8	15[c]	5
Bagasse	1,900	7600	—
Pollution costs	—	—	60
Total		9917	301

[a] Outputs: 1000 L of ethanol = 5,130,000 kcal.

[b] Table 20.11.

[c] Slesser and Lewis (1979).

TABLE 20.11
Average Energy Input and Output per Hectare per Year for Sugarcane in Brazil[a]

	Quantity/ha	10^3 kcal/ha	Dollars/ha[b]
Inputs			
Labor	210 h[c]	157[d]	120
Machinery	72 kg[e]	1944	119
Fuel	262 L[f]	2635	131
Nitrogen (ammonia)	65 kg[f]	1364	42
Phosphorus (triple)	52 kg[f]	336	27
Potassium (muriate)	100 kg[f]	250	27
Lime	616 kg[f]	192	92
Seed	215 kg[e]	271[d]	70
Insecticide	0.5 kg[f]	50	5
Herbicide	3 kg[f]	300	30
Total		7499	663
Output			
Sugarcane	54,000 kg[f]	15,120,000	
Sugar yield	3672 kg		

[a] kcal input/kcal sugar = 2.02.

[b] Calculated based on quantity of inputs.

[c] Calculated from footnote b.

[d] Ghirardi (1983).

[e] Similar to Louisiana (Table 20.9).

[f] da Silva et al. (1978).

so would add 20% to the cost (Nastari, 1983). Sugarcane feedstock accounts for 56% of the total production costs. Further, inputs include the costs for controlling pollution. The BOD of wastewater from Brazilian sugarcane-based alcohol plants has an environmental impact equal to about two-thirds of the wastes produced by the total human population in Brazil (Desai et al., 1980).

In the Brazilian ethanol production system, 2.6 ha per year of land is needed to fuel one automobile (Tables 20.10 and 20.11). Therefore, if all the automobiles in Brazil were fueled using sugarcane-produced ethanol, a total of 26 million ha of cropland would be needed. This amounts to more than one-third of the total cropland now in production (Table 20.2).

FUELWOOD AND OTHER SOLID BIOMASS FUELS

The oldest and simplest use for biomass fuel is cooking and heating. Firewood is the most common form of biomass used. In many environments, wood is readily available and can be easily cut and transported to people's homes. It is easily stored and burns slowly.

Firewood supplies have declined in many parts of the world, creating a need on the part of farmers, governments, development agencies, and many others to promote reforestation to improve the firewood supply (Allen, 1986) Generally, these efforts have been categorized under the titles "social forestry" and "agroforestry" and help increase farmer access to wood supplies outside traditional forest systems.

Social forestry, or community forestry, has received much publicity and has been favored by large donor organizations because they feel large forests have a greater visible impact than numerous scattered, small farm woodlots (Khoshoo, T.N., personal communication, New Delhi: Tata Energy Research Institute, 1987). However, social forest projects have not been successful for many reasons (Allen, 1986; Khoshoo, 1987). First, the people planting and caring for the trees do not have the same interest in these plantings as they usually have in their own trees. They tolerate grazing and other activities, and as a result large portions of these forests have been destroyed. Second, harvesting in such a large area is difficult to control and regulate; people who live close to the forest typically harvest a large share of the wood. Third, many people who depend on the social forests must travel long distances to cut; transport their wood. Together these factors have made social forests much less effective than farm woodlots (Allen, 1986).

Agroforestry is the deliberate management of trees on a given piece of land in association with crops, livestock, or a combination of the two (Teel, 1984). In many situations it has been demonstrated that, although the productivity of a given component may decrease in an agroforestry system, the overall productivity of the entire system increases (Kidd and Pimentel, 1992). Agroforestry should not be regarded as the only strategy for providing energy resources for all the rural poor. It is not appropriate for certain areas, such as the rice-growing regions of India, where population densities of people and animals make the survival of trees nearly impossible. There people have had to use locally available biomass, such as crop residues and dung, as fuel. But dung has value as a fertilizer and in protecting the soil from erosion. The manure and urine of milk cows contains

19.5% nitrogen by dry weight (Jewell et al., 1977) and 3.6 million kcal/ton of heat energy (Bailie, 1976). About 195 kg of nitrogen fertilizer is lost for every ton of dry dung burned. Replacing this nitrogen fertilizer, which has an energy value of 2.87 million kcal/ton, costs $0.53/kg, or $103/ton. These values do not include the replacement costs for phosphorus, potassium, and calcium, because these are assumed to be recovered from the ash or as loss to the soil of the organic material in the manure.

Burning crop residues for energy has been proposed. However, many environmental problems are associated with this practice, which involves removing the vegetative covering, a protective layer that significantly decreases soil erosion and water runoff. For example, soil erosion rates may increase 90% when crop residues on soil surfaces are reduced from about 6 t/ha to 0.5 t/ha (Mannering, 1984). Water runoff rates increase 10–100 times when vegetative cover is removed from the land (USDA-ARS and EPA-ORD, 1976). In certain localized land areas that can tolerate some loss of organics without an increase in erosion, crop residues could be an energy source. However, under current agricultural practices in the United States and elsewhere, little or no crop residue should be burned for fuel (ERAB, 1981; Pimentel et al., 1981, 1987).

Burning crop residues is more complicated and costly than burning coal. More work hours are required to tend and stoke the furnace to prevent clogging, control air flow to the chamber, clean the ash, and add small, constant amounts of fuel (Bailie, 1976). Although about 12.5 kg of crops residues equals 1 kg of fuel oil in energy terms, about double the amount of energy is used to obtain the same heat value because of the energy-intensive burning process (OECD, 1984).

BIOGAS

Biomass material that contains large quantities of water can be effectively converted into usable energy using naturally occurring microbes in an anaerobic digestion system. These systems are presently used with dung and certain plants, such as water hyacinth (though production and harvesting problems are greater with the latter). The system is comparatively simple, utilizing mesophilic bacteria, with an overall construction cost of around $600 (Teel, W., personal communication, Department of Natural Resources, Cornell University, Ithaca, NY, 1987), or complex systems for 320-cow operations costing $120,000 or more for construction (SF, 1983). The basic principles for both are similar.

On a small dairy or cattle operation, manure is loaded or pumped into a sealed, corrosion-resistant digestion tank and held there for 14–28 days at temperatures around 30°C–38°C. In some systems, the manure in the tank is constantly stirred to distribute heat and speed the digestion process. During this period the mesophilic bacteria present in the manure break down volatile solids, converting them into methane gas (65%) and carbon dioxide (35%). Small amounts of hydrogen sulfide may also be produced. These gases are then drawn off through pipes and either burned directly, in the same way as natural gas, or scrubbed to eliminate the H_2S and used to generate electricity. The cost breakdown for one system is listed in Table 20.12.

TABLE 20.12
Energy Inputs Using Anaerobic Digestion for Biogas Production from 100 t Wet (13 t Dry) Cattle Manure[a]

	Quantity	10^3 kcal
Inputs		
Human hours[b]	20 h	—
Electricity	2234 kWh[c]	5822[d]
Cement foundation[e] (30-year life)	0.9 kg[c]	2[f]
Steel (gas collector[e] and other equipment with 30-year life)	35 kg[c]	725[g]
Pumps and motors[h]	0.05 kg[c]	1[g]
Steel truck/tractor[b] for transportation (10-year life)	10 kg[c]	200[g]
Petroleum for transport[b] (10 km radius)	34 L[c]	340[i]
Total		7090
Total output		10,200[j]

[a] The retention time in the digester is 20 days. The unit has the capacity to process 1825 t (wet) per year. The yield in biogas from 100 t of manure (wet) is estimated at 10.2 million kcal. Thus, the net yield is 3.1 million kcal (Pimentel et al., 1978). The energy for heating the digester is cogenerated, coming from the cooling system of the electric generator.

[b] Estimated.

[c] Vergara et al. (unpublished data).

[d] 1 kWh = 860 kcal. Based on an energy conversion of fuel to electricity of 33%; thus, 1 kWh is equivalent to 2606 kcal.

[e] The digester was placed underground. Materials used for its construction were concrete and steel. Materials also included a gas storage tank.

[f] 1 kg of cement = 2000 kcal for production and transport (Lewis, 1976).

[g] 1 kg of steel = 20,700 kcal for mining, production, and transport (Pimentel et al., 1973).

[h] The design included three electrical devices: a motor to drive the agitator in the digester, a compressor to store gas, and a pump to supply hot water.

[i] A liter of fuel is assumed to contain 10,000 kcal. Included in this figure are mining, refining, and transportation costs.

[j] It was assumed that anaerobic digestion of manure takes place at 35°C, with a solids retention time of 20 days. The temperature of the fresh manure is taken as 18°C and the average ambient temperature as 13°C. The manure is assumed to have the following characteristics: production per cow per day, 23.6 kg total; solids, 3.36 kg; biological oxygen demand (BOD), 0.68 kg. The digestion is assumed to transform 83% of the biodegradable material into gas. Gas produced is said to be 65% methane, and its heat of combustion is 5720 kcal/m^3 at standard conditions.

The amount of biogas produced is determined by the temperature of the system, the manure's volatile solids content, and the efficiency of converting them to biogas. This efficiency varies from 18% (Jewell and Morris, 1974) to 95% (Jewell et al., 1977). Dairy cows daily produce 85 kg of manure per 1000 kg live weight. The total solids in this manure are 10.6 kg and of these 8.6 kg are volatile solids. Theoretically, a 100% efficient digester would produce 625 L of biogas from every 1 kg of volatile solids added (calculated from Stafford, 1983). The digester utilized for the data in Table 20.12 was 28.3% efficient, producing 177 L of biogas/kg of volatile solids added. With this digester 1520 L of biogas per 1000 kg live weight will be produced each day. If the total heat value of the manure were used in calculating efficiency, then the efficiency rate would be only 5%.

Biogas has an energy content of about 5720 kcal/m^3, less than the 8380 kcal/m^3 for pure methane because of the carbon dioxide present. When processed into biogas, 100 t of manure (wet weight) yields a total of 10.2 million kcal; the process itself requires 7.1 million kcal energy, so the net energy yield is 3.1 million kcal (Table 20.12). Much of the energy cost comes from the production of electricity to run the pumps and the stirring system used to reduce the retention time in the digester. The volume of the digester is determined by the amount of manure produced by the animals during the usual retention time. In this example, with a retention time of 14 days, the volume would be slightly more than 75 m^3. It is assumed that this added electric energy will be generated from the biogas itself and that the conversion efficiency of this operation is 33%. The energy needed to heat the digester is cogenerated by the electric generator via the use of the generator's cooling system. The net energy produced by the digester can be used either to generate electricity for the farm or as a heat source.

When the biogas is not used to produce electricity, the energy data listed in Table 20.12 will change considerably, and other costs will be associated with the changes. The heat requirements were calculated by including the heat losses to the surroundings, the heat associated with the feed and the effluents, and the heat generated by the biological reaction. Processing biogas for use in engines involves significant amounts of added energy for compression and for removal of hydrogen sulfide and water.

Although material costs are lowered if there is no generator or stirring mechanism on the digester, the size of the digester must be increased because the retention time increases. Also, more of the biogas will have to be used to heat during the extended retention time, as much as 610,000 kcal for every 100 t of wet manure digested (Vergara et al., 1977). In the tropics the overall efficiency of biogas systems is enhanced because the system does not have to be heated.

Dairy cattle are not the only source of manure for biogas systems. They are used as a model because they are more likely to be located in a centralized system, making the process of collecting the manure less time-consuming and energy-intensive than for range-fed steers or even for draft animals. Efficiencies of conversion vary not only from system to system but also from animal to animal (Stafford, 1983). Swine and beef cattle manure appear to yield more gas per kilogram of volatile solids than dairy cattle manure. Poultry manure is also a good source, but sand and other forms of heavy grit in their dung cause pump maintenance problems.

Manure that exits the digester retains its fertilizer value and has less odor than undigested manure. It can be spread on fields in the usual way and may be easier to pump if a cutter pump is used to break up stray bits of straw or long undigested fibers. Biogas systems can easily be adapted in size according to the scale of the farm operation. However, the pollution problem associated with manure produced in centralized dairy production systems remains.

BIOGAS FOR SMALL LANDHOLDERS

The costs and benefits of biogas production in a rural area of a developing nation such as Kenya or India are mixed. The capital costs of constructing a simple biogas

TABLE 20.13
Energy Inputs for an Anaerobic Digester for Biogas Production Using 8 t Wet (1 t Dry) Cow Manure[a,b]

	Quantity	kcal
Output from 1 t biomass (dry) methane gas	143 m^3	820,000[c]
Inputs for 1 t biomass		7140
Cement foundation (30-year life)	0.07 kg[d]	140[e]
Steel (30-year life)	0.33 kg	7000[f]
Net return/ton dry biomass		812,860

[a] The retention time is 20 days without a means of storing the methane gas (Pimentel, unpublished data).

[b] Efficiency = (812,840 kcal output)/(4.7 × 10^6 kcal input) × 100 = 17.3%. The input is the energy content of manure if burned.

[c] It was assumed that anaerobic digestion of biomass takes place at 35°C with a solids retention time of 20 days. The temperature of the fresh biomass and the average ambient temperature are taken as 21°C. The efficiency of the digester is 25%. Gas produced is said to be 65% methane, and its heat of combustion is 5720 kcal/m^3.

[d] Vergara et al. (unpublished data).

[e] 1 kg of cement = 2000 kcal for production and transport (Lewis, 1976).

[f] 1 kg of steel = 21,000 kcal for mining, production, and transport (Pimentel et al., 1973).

digester with a capacity to process 8 t (wet) of manure per 20-day retention period, or 400 kg per day (Table 20.13), are estimated to be $2000–$2500. Because the unit would have a life of 30 years, the capital cost would be about $80 per year. If rural workers were to construct the generator themselves, material costs might range from $300–$600. If we assume $400, the capital investment would be only $14 per year for the life of the digester.

A digester this size in India, where the cows are much smaller and produce only 225–330 kg manure each per 20 days, would require access to 20 cows. With a conversion rate of 25% (Table 20.13) this amount of manure would produce an estimated 2277 m^3 of biogas per year with an energy value of 13.0 million kcal. Assuming $8.38/million kcal, the value of this much energy would be $109. If no charge is incurred for labor and dung, and the capital cost is only $14/year, the annual net saving is $95.

Although the labor requirement for running the generator described is only 5–10 min per day, the labor input for collecting and transporting biomass for the generator may be significant. For instance, if the required 400 kg of manure had to be transported an average of 3 km, it would take two laborers a full 8-h day to collect it, feed it into the digester, and return it to the fields where it could be utilized as a fertilizer. The laborers would have to work for about $0.03/h to keep labor costs equal to the value of the gas produced. However, in densely populated areas or with centralized systems, the amount of transport would be minimal.

Although the profitability of small-scale biogas production may be low even without labor costs, digesters have advantages, especially in rural areas. Manure biomass can be processed and fuel energy can be obtained without loss of the valuable nutrients (nitrogen, phosphorus, potassium, and sulfur). Nitrogen and phosphorus are major limiting nutrients in tropical agriculture. The only change in the manure is the breakdown of its fibrous material, making it less effective in controlling soil erosion (Pimentel, 1980). By contrast, when manure is burned directly as a fuel, nitrogen and other valuable nutrients are lost to the atmosphere. The biogas slurry from the U.S. cattle example (146 t/year) contains approximately 3.7 t of nitrogen. This has an energy value of 77 million kcal and, as chemical fertilizer, a market value of $1960 ($0.53/kg) (USDA, 1991b). Therefore, producing biogas is more cost effective than burning manure. When the value of the retained nitrogen and the gas output are combined, the return of the system is about $6.42/h of work.

Another consideration in assessing the use of biogas production is the possibility of replacing firewood with biogas as an energy resource. The production of 2277 m^3 of biogas (13.0 million kcal) would replace 3 t of firewood, which has an average energy value of 4500 kcal/kg (NAS, 1980). Because gas is more efficient than wood for cooking (heating), the amount of wood replaced could double. In areas where wood is scarce, biogas could diminish reliance on wood and slow deforestation.

SOCIOECONOMIC FACTORS

Promoters of biomass energy emphasize its benefits to society, the economy, and the environment (Hall et al., 1985; Sourie and Killen, 1986). These include the creation of jobs, increased economic development, reduction in energy cost, debt reduction, and the use of indigenous technology. In this section we attempt to make a detailed analysis of the socioeconomic benefits and costs of the Brazilian alcohol fuels program, which is frequently cited as demonstrating the benefits of biomass energy. In addition, some data are presented on the socioeconomic impact of biomass energy use in the United States.

BRAZIL

The Brazilian alcohol program, PROALCOOL, is held up as a model of how developing countries can meet their fuel oil needs using renewable biomass resources such as sugarcane. Alcohol production appeared to be an elegant solution to many problems faced by developing countries in the early 1970s. Substituting a homegrown energy resource for costly imported fuel made sense. Sugarcane had been cropped in Brazil since the earliest days of colonization, and Brazilians had conducted research on alcohol production from sugar. Because the concept sounded so sensible and the press coverage was so good, PROALCOOL moved ahead rapidly with little or no criticism.

Analyzing the socioeconomics of Brazilian alcohol production is complicated. Not only must the relationship between the price and elasticity of demand for sugar, alcohol, and gasoline be carefully examined, but this must be done within the context of often rapid inflation and with the limited data provided by the Brazilian government. Although a total analysis is needed, this assessment focuses on the costs of alcohol production in Brazil and the known effects of alcohol production on food prices, food availability, and employment.

By all accounts appearing in the literature, the costs of alcohol production are higher than the price Petrobras charges retailers for alcohol (Ortmaier, 1981). Thus, the Brazilian government must subsidize to make up the difference. Of course, pricing depends on the world prices for sugar and gasoline at any given time. The Ministry of Industry and Commerce published the statement that 56% of the cost of alcohol production was assigned to the purchase of sugarcane, resulting in a production cost of $0.33/L (Pimentel et al., 1988).

The high cost of production necessitated government subsidies for alcohol producers. According to Nastari (1983), from 1976 to 1980 subsidies reached 61 billion cruzeiros, or about $490 million per year. Alcohol producers increased their gross income by more than 200% in this same time period (Nastari, 1983). Although the large subsidies contribute significantly to the Brazilian debt, ethanol production helps the government reduce the amount of foreign exchange expended to import oil. Brazil imports about 39 million L, or $9 billion worth, of oil annually and has to pay an interest rate of about 4.7% per annum on all borrowed money (World Development Report, 1995). Thus, the production of 9.1 L of ethanol helps reduce the amount of oil imported and, in turn, the level of costly borrowing. However, 1 L of ethanol does not equate to 1 L of imported oil. About 0.5 L of oil equivalent has to be imported to produce 1 L of ethanol.

A fundamental economic issue generated by the PROALCOOL program is the relationship among alcohol production, the price, and the availability of food. This matter is usually discussed only in terms of the relative proportion of land devoted to energy crops and food crops. The question is particularly complicated in a country such as Brazil, which has abundant cropland and the capacity to provide far more food than its population can consume. Despite the availability of this cropland, 25% of Brazil's population is malnourished (Calle and Hall, 1987).

Many factors determine the price and availability of foods, but supply and demand are the primary ones. From 1971 to 1980 an increasing percentage of land was planted to sugarcane and export crops, including soybeans, whereas the percentage of land with food crops remained constant from 1976 to 1980 (Table 20.14).

TABLE 20.14
Trends in Areas under Sugarcane and Other Crops in Brazil from 1971 to 1980[a]

	1971–1973	1975	1976	1977	1978	1979	1980
Alcohol production (10^6 L)[b]	654	556	664	1,470	2,491	3,396	3,786
Area under sugarcane (10^3 ha)	1,830	1,969	2,093	2,270	2,391	2,537	2,607
Soybeans (10^3 ha)	2,507	5,824	6,417	7,070	7,782	8,256	8,766
Food crops (10^3 ha)[c]	24,659	25,837	28,036	28,270	26,922	27,542	28,030
Export crops (10^3 ha)[d]	12,951	15,566	14,526	16,730	17,789	18,408	18,949
Total cultivated area (10^6 ha)	37.3	42.0	43.3	45.7	45.5	46.8	47.9

[a] OECD (1984).

[b] Production from May of the year concerned until April of the following year.

[c] Rice, potatoes, beans, manioc, maize, wheat, bananas, onions.

[d] Cotton, groundnuts, cocao, sissal, coffee.

Between 1973 and 1980 black bean production declined by 16% and sweet potato production declined 56% (OECD, 1984). From 1976 to 1981, the total area planted for three basic staple crops—maize, rice, and black beans—remained stable at about 1.9 million ha (Pluijm, 1982). During this period the Brazilian population increased by about 15 million people (PRB, 1977), increasing food demand by about 12%.

In São Paulo state, where 70% of the alcohol is produced, significant changes have taken place in agriculture since the start of the PROALCOOL program. Sugarcane production increased by 1.1 million ha from 1968/1969 to 1982/1983, whereas acreage planted in food crops declined by 0.4 million ha during the same period (excluding soybeans that are exported) (Calle and Hall, 1987). About 60% of the expansion in sugarcane acreage came from reclaimed pastureland, adversely affecting milk and meat supplies. In this same period, export crop acreage increased by 0.2 million ha, further diminishing acreage used for domestic food crop and milk/meat production (Calle and Hall, 1987).

The stagnant levels of food production in Brazil overall and growing food demand have led to reduced availability and high prices of food (La Rovere, 1985). In 1976 riots broke out in Rio de Janeiro over a shortage of the local staple, black beans, coupled with general political and economic unrest (Goldemberg, 1987). The decline in black bean availability led to the importation of black beans from Chile. The cycle continued, with increases in alcohol production and export crops, accompanied by a decline in per capita output of major staple food crops. At the same time, food prices increased more than the general inflation rate, an occurrence without precedent in Brazil's economic history (La Rovere, 1985).

An additional incentive to produce sugarcane and alcohol was provided by the rapidly escalating value of land located near distilleries. Land prices in Brazil for producing sugarcane rose to about $1500/ha (Ghirardi, 1983). With the income of the Brazilian laborer estimated to be about $1000/year, it would take a laborer many years to save sufficient money to purchase even 1 ha of land. Increased land values also encouraged smallholders, who usually grow food crops for domestic consumption, to sell their land to large sugarcane growers, thereby expanding the land area devoted to sugarcane (Pluijm, 1982). Because most distilleries are located close to towns and urban centers, basic food production has moved farther away from food consumers, increasing the energy costs of transport and contributing to higher food prices.

The workplace and wages were also affected by the PROALCOOL program. Landless agricultural workers who live on the periphery of cities accept almost any job they can find, often being trucked to rural areas each day to work in the fields (Desai et al., 1980). Thousands of small farmers were transformed into landless laborers during a period in which food production for the domestic market was stable. Small farmers provide the bulk of their own subsistence. The displacement of small subsistence farmers meant food production for domestic consumption would have to increase to enable these workers to eat as they once did. This did not occur. Instead, about 40% of the Brazilian labor force now earns a minimum wage of about $100/month, or about $0.63/h. Basic foods per month for a family cost three times this wage (World Tables, 1995).

Another aspect of the food-versus-fuel question is employment. According to Ortmaier (1981), 51% of the land converted to sugarcane in 1975 previously had been planted to food crops. Whenever sugarcane production replaced a more labor-intensive crop or a crop providing year-round employment, a net loss of jobs resulted.

Typically, sugarcane/alcohol production work is highly seasonal, resulting in at least 50% unemployment among sugar and alcohol workers during the 4-month off-season (OECD, 1984). Only when sugarcane production is accompanied by diversified agricultural production can people find steady work. This is not the usual practice.

Projections concerning the creation of jobs because of the ethanol program were encouraging. The World Bank (1980) reported that 1 new job would be created for each 20,000 L of alcohol produced and that 172,000 new jobs would be created if alcohol production was increased by about 7 billion L. A similar trend was suggested by Pereira (1983). OECD (1984) projected that 27,700 jobs would be created if the increased production was from large alcohol plants (production of up to 120,000 L of alcohol per day). However, other analysts reported that the overall increase in employment was not as great as anticipated, with far fewer jobs created than either the World Bank or the Brazilian government projected (OECD, 1984).

Obviously, the 25% of the people who are malnourished (Calle and Hall, 1987) and the 40% who are unemployed have not benefited from the Brazilian alcohol program. Their plight contrasts sharply with the 10% of the people who own cars and have benefited from low fuel costs of the subsidized ethanol program (Kurian, 1995).

UNITED STATES

Although biomass production in the United States has certain problems (Pimentel, 1991), it will provide at least one advantage—some increased employment. For example, the direct labor inputs for wood biomass resources are 2–30 times greater per million kcal energy produced than for coal (Pimentel et al., 1983a); thus, wages would be lower for workers in biomass production. A wood-fired steam plant requires two to five times more construction workers and three to seven times more workers per plant. Total employment overall would be expected to increase from 5% to 20% depending on the quantities of biomass used and general economy of the nation.

However, a shift to more biomass energy production can be expected to increase occupational hazards in the industry (Morris, 1981). Significantly more occupational injuries and illnesses are associated with biomass production in agriculture and forestry than with either coal (underground mining), oil, or gas recovery operations (OTA, 1980). Agriculture has the highest rate of injuries—25% more injuries per day of work than any other private industry (OTA, 1980). The total injury rate in logging and other forest industries annually averages about 25 per 100 full-time workers, whereas it is about 11 for bituminous coal miners, who work mostly underground (BLS, 1978, 1979, 1980, 1981). Per kilocalorie output, forest biomass production has 14 times more occupational injuries and illnesses than underground coal mining and 28 times more than oil and gas extraction (BLS, 1978).

Food and lumber products have a higher economic value per kilocalorie in their original form than when converted into either heat, liquid, or gaseous energy (ERAB, 1980, 1981; OTA, 1980). For example, 1 million kcal of corn grain has a market value of $40, but when converted to heat energy it has a value of only $5. Producing liquid fuels (e.g., ethanol) is also expensive. A liter of ethanol now costs about $0.40 to produce; nearly 65% of the cost of production is for the grain itself (Pimentel et al., 1991).

Subsidies help make gasohol competitive with gasoline. Federal and state subsidies may range as high as $0.36/L for U.S. ethanol (OTA, 1980). As a result, when production and subsidies are included, a liter of ethanol costs $0.83, compared with the $0.15 cost of a liter of gasoline at the refinery (Pimentel, 1991). For the equivalent of 1 L of gasoline (8000 kcal), 1.5 L of ethanol (5310 kcal/L) would be needed, with a total value of $1.25.

The real cost to the consumer is greater than the $0.83 needed to produce a liter of ethanol because 50% of all grain consumed in the United States is fed to livestock (WRI, 1994). Therefore, shunting corn grain into ethanol will increase the demand for grains, resulting in higher grain prices. Higher grain prices will in turn raise the consumer prices of meat, milk, and eggs (ERAB, 1980).

ENVIRONMENTAL IMPACTS

The removal of biomass from land for energy production increases the effects of wind and water on soil degradation. Erosion and increased water pollution and flooding disrupt many wildlife communities and may adversely affect the health of some human populations.

Soil Erosion Problems in Biomass Systems

It is difficult to derive biomass for energy use from crops such as corn, sugarcane, wheat, and rape grown on sloping land that is unsatisfactory for agriculture (Figure 20.1). High

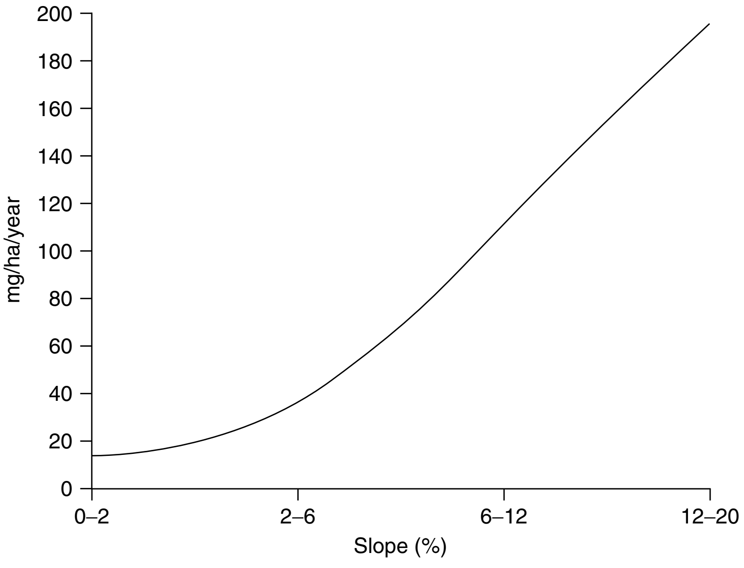

FIGURE 20.1 Increased soil erosion rates (mg/ha/year) associated with rising land slope percentages.

erosion rates for these crops occur even when biomass residues are left on the land (Table 20.15). If these crop residues are harvested for fuel, the erosion rates increase (Pimentel et al., 1981). For example, leaving 6.7 t/ha of corn residues on land will keep erosion rates at 1–1.6 t/ha when no-till planting is employed. However, if 4–5 t/ha of residues are removed, soil loss increases about eight times (Table 20.16). This latter erosion rate is about 14 times greater than the soil re-formation rate (Pimentel et al., 1987). The production of forage and hay crops for energy is possible on land with slopes of up to 12%, provided that care is taken to maintain a dense stand of vegetation cover and that good management practices are employed in the harvesting of biomass (ERAB, 1981). Unless steps are taken to protect soil, the removal of crop residues from slopes of 2% or greater would seriously degrade soil resources.

Soil erosion rates of undisturbed forests, with their dense soil cover of leaves, twigs, and other organic material, typically range from less than 0.1 to 0.2 t/ha/year (Megahan, 1972, 1975; Dissmeyer, 1976; Patric, 1976; USFS, 1977; Yoho, 1980; Patric et al., 1984). These conditions make most natural forest soils, even those on steep slopes of 70%, fairly resistant to erosion and rapid water runoff.

Forests lose significant quantities of water, soil, and nutrients when the trees are cut and harvested. For instance, the surface runoff after a storm from a forested watershed averages 2.7% of the precipitation; after forest cutting and farming, water runoff rises to 4.5% (Dils, 1953). Clear-cutting of trees without harvest and without soil disturbance causes flood damage from high stream flow to occur 10% more often than with the normal forest stand (Hewlett, 1979). Replacing natural forest growth with coppice forest regrowth increases annual stream flow about 10 cm above normal (Swank and Douglass, 1977). Nitrogen leached after forest removal may be six to nine times greater than in forests with normal cover (Hornbeck et al., 1973; Patric, 1980).

In any area, harvesting timber and pulpwood greatly increases erosion, because covered land becomes exposed and the clearing process disturbs the soil. Typically, tractor roads and skid trails severely disturb 20%–30% of the soil surface (Megahan, 1975; Froelich, 1978). Harvesting techniques such as highland and skyline disturb 10%–20%, whereas balloon harvesting disturbs only about 6% of the land area (Rice et al., 1972; Swanston and Dyrness, 1973). Further, the heavy equipment used compacts the soil, causing increased water runoff.

For example, compaction by tractor skidders harvesting ponderosa pine reduce growth in pine seedlings from 6% to 12% over a 16-year period (Froelich, 1979). Water percolation in wheel-rutted soils is significantly reduced for as long as 12 years and in log-skid trails for 8 years (Dickerson, 1976). This creates a long-range problem, because lack of water is the major limiting factor in forest biomass production. Growth of slash pine in Florida over a 5-year period with irrigated treatment is 80% greater than in the untreated acreage (Baker, 1973). Depending on slope, soil type, and climate, the effects of soil compaction on tree growth may last from 8 to 16 years (Dickerson, 1976; Froelich, 1979).

Though erosion rates can be as high as 215 t/ha/year on severely disturbed slopes, average soil erosion in harvested forests ranges from 2 to 17 t/ha/year, with long-term averages between 2 and 4 t/ha/year (USFS, 1977; Yoho, 1980; Patric, 1976). Erosion from conventional logging can last for 20 years, but the most serious erosion ceases in about 5 years, when vegetation cover becomes established (Patric,

TABLE 20.15
Selected Erosion Rates in Certain Geographical Regions

Country	Erosion Rate (t/ha/year)	Comments	Sources
United States	13[a]	Average, all cropland	USDA (1994)
Midwest, deep loess hills (Iowa and Missouri)	35.6[a]	MLRA[b] # 107, 2.2 million ha	Lee (1984)
Southern high plains (Kansas, New Mexico, Oklahoma, and Texas)	51.5[a]	Lee (1984) MLRA[b] # 77, 6.2 million ha	
Brazil	150	Beans grown up and down slope	Silva et al. (1985)
	12	Beans grown with agroforestry	
India	25–30	Cultivated land[c]	DST (1980)
	28–31	Cultivated land	Narayana and Babu (1983), CSE (1982)
Deccan black soil region	40–100		
China	43	Average, all cultivated land middle reaches, cultivated rolling loess	Brown and Wolf (1984)
Yellow River basin	100	Brantas River basin	AAC (1980)
Java	43.4		Brabben (1981)
Belgium	10–25	Central Belgium, agricultural loess soils	Bollinne (1982; in Richter, 1983)
East Germany	13	1000-year average, cultivated loess soils in one region	Hempel (1951, 1954; in Zachar, 1982)
Ethiopia	20	Simien Mountains, Gondor region	Lamb and Milas (1983)
Madagascar	25–40	Nationwide average	Randrianarijaona (1983); Finn (1983)
Nigeria	14.4	Imo region, includes uncultivated land	Osuji (1984)
El Salvador	19–190	Acelhuate basin, land under basic grains production	Wiggins (1981)
Guatemala	200–3600	Corn production in mountain region	Arledge (1980)
Thailand	21	Chao River basin	El-Swaify et al. (1982)
Burma	139	Irrawaddy River basin	El-Swaify et al. (1982)
Venezuela and Colombia	18	Orinoco River basin	El-Swaify et al. (1982)

[a] Indicates combined wind and water erosion, all others are water erosion only.

[b] MLRA: major land resource area.

[c] Assumes that 60%–70% of the 6 million tons of topsoil lost is from cultivated land.

TABLE 20.16
Percentage of Soil Loss from Several Conservation Tillage Systems Compared with Conventional Tillage on Land with Continuous Corn Culture[a]

	Surface Residue after Planting (%)				
Tillage System	**1.1–2.2 t/ha**	**2.2–3.4 t/ha**	**3.4–4.5 t/ha**	**4.5–6.7 t/ha**	**Over 6.7 t/ha**
Till planting (chisel, disk)	89	61	48	33	20
No till	71	48	33	18	8

[a] Continuous corn with conventional tillage on land with a slope of 2% or more will suffer about 20 t/ha/year soil erosion.

Source: Mannering, J.V., Agronomy Guide (Tillage) AY–222, Cooperative Extension Service, Purdue University, West Lafayette, IN, 1984.

1976). Although erosion caused by forest harvesting is not great compared to that associated with row crop production, its effects can be long-lasting because of the extremely slow rate of soil formation in forest ecosystems. The nutrients lost when topsoil is eroded also affect forest growth. Losing 3 cm of soil surface reduces biomass production in ponderosa pine, Douglas fir, and lodgepole pine seedlings as much as fivefold (Klock, 1982).

As the need to produce more biomass for energy becomes critical in countries such as Brazil, more land will have to be placed under cultivation to supply it. If this additional land is taken from food crop acreage, farmers may be forced to clear forests or use poor-quality cropland in an effort to maintain or augment the level of food production to feed the expanding human population. Utilization of poor-quality land for crops only will further intensify soil erosion rates. Often these marginal lands are on slopes, making them highly susceptible to erosion when planted to crops.

NUTRIENT LOSSES AND WATER POLLUTION ASSOCIATED WITH BIOMASS ENERGY AND EROSION

Rapid water runoff and soil nutrient losses occur when crop residues are harvested and subsequent rainfall erodes soils. Water quickly runs off unprotected soil because raindrops free small soil particles, which in turn clog holes in the soil and further reduce water infiltration (Scott, T.W., personal communication, Department of Agronomy, Cornell University, Ithaca, NY, 1985). For example, conventional corn production causes an average of about 5 cm/ha/year more water runoff than production employing conservation practices (Pimentel and Krummel, 1987). Harrold et al. (1967) reported that under conventional corn production, erosion reduced soil moisture volume by about 50% compared with no-till corn culture. Rapid water runoff not only diminishes the amount of water reaching plant roots, it also carries valuable nutrients, organic matter, and sediments with it. Soil nutrient losses have a major negative effect on soil quality. One ton of fertile agricultural soil contains about 4 kg of nitrogen, 1 kg of phosphorus, and 20 kg of potassium (Buttler, I., personal communication, Department of Agronomy, Cornell University, Ithaca, NY, 1986). Based on these soil nutrient values

TABLE 20.17
Nitrogen, Phosphorus, and Potassium Content of Crop Residues and Firewood

	Nutrient Content (%)		
	Nitrogen	Phosphorus	Potassium
Corn[a]	1.1	0.2	1.3
Rice[a]	0.6	0.1	1.2
Wheat[a]	0.7	0.1	1.0
Soybean[a]	2.3	0.2	1.0
Sugarcane[a]	1.0	0.3	1.4
Firewood[b]	0.12	0.01	0.06

[a] Power and Papendick (1985).
[b] Pimentel et al. (1983b).

and average U.S. erosion rate of 18 t/ha/year, erosion causes an average yearly loss of about 72 kg/ha of nitrogen, 18 kg/ha of phosphorus, and 360 kg/ha of potassium.

When conservation technologies are employed by protecting the soil with residues and vegetation, increased crop yields result because water, nutrients, and soil organic matter are retained. For example, in Texas, yields of cotton grown on the contour and with ample soil protection are 25% greater than from cotton grown with the slope (Burnett and Fisher, 1954). Similar results have been reported for corn (12.5%) in Missouri (Smith, 1946) and for corn (12%), soybeans (13%), and wheat (17%) in experiments in Illinois (Sauer and Case, 1954). On land with a 7% slope, yields from cotton grown in rotation increase 30%, and erosion is cut nearly in half (Hendrickson et al., 1963). In Nigeria, yields from no-till corn grown under favorable soil and climatic conditions are 61% greater than from corn grown with conventional tillage (Wijewardene and Waidyanatha, 1984). In an experiment comparing tillage practices used on 22 consecutive maize crops grown on highly erodible Nigerian soils, the average grain yields from no-till plots were 20% higher than those from conventional plots because of the accumulated effects of erosion-induced degradation of the unprotected soil (Lal, 1983).

When crop residues are removed and burned, significant quantities of nutrients are lost. On average, residues contain about 1% nitrogen, 0.2% phosphorus, and 1.2% potassium (Table 20.17). When burned, the nitrogen volatilizes into the atmosphere, and 70%–80% of the phosphorus and potassium is lost with the particulate matter during the process (Flaim and Urban, 1980). Thus, a relatively small percentage of the nutrients in crop residues would be conserved, even if the ash residue were returned to the cropland.

AIR POLLUTION

The smoke produced when firewood and crop residues are burned for energy contains nitrogen, particulates, and other chemicals, making it a serious pollution hazard. A recent EPA report (1986) indicated that although burning wood provides only about 2% of U.S. heating energy, it causes about 15% of the air pollution in the United States. Emissions from wood and crop residue burning are a threat to public health, because of the highly respirable nature of some of the 100 chemicals the emissions contain (Pimentel et al., 1983a). Of special concern are the relatively high concentrations of potentially carcinogenic polycyclic organic compounds (POMs, e.g., benzo(a) pyrene) and particulates. Sulfur and nitrogen oxides, carbon monoxide, and aldehydes are also released, but usually in smaller quantities (DOE, 1981; Morris, 1981). According to the Department of Energy (1980), wood smoke contains "up to 14 carcinogens, 4 co-carcinogens, and 6 cilia toxic and mucus coagulating agents." Concern is being expressed for people in developing nations who cook indoors, breathing in the smoke released by burning wood, dung, and crop residues.

The concerns of inhaling wood smoke have been particularly great in India, where people commonly cook in inefficient stoves known as *chullahs* without venting the smoke from the house. Wood smoke, as mentioned, contains many dangerous chemicals, including carbon monoxide, which has been associated with poor fetal development and heart disease in Indian women (Sharma, 1987). Sharma (1987) also reported that women are routinely exposed to chemicals and suspended particulate matter levels as much as 10 times higher than safe public health levels.

Air particulates increase when dung is used in addition to or in place of wood as a fuel (CSE, 1985). However, biogas can be a healthier energy option for cooking than dung. In India, 1000–1050 Mt of wet dung is available from 237 million cattle for recycling into biogas. The 206 Mt/year of manure slurry provides about 1.4 Mt of nitrogen, 1.3 Mt of phosphate, and 0.9 Mt of potash for the soil (Khoshoo, 1986). As of 1992, approximately 1.4 million biogas plants were operational in India; their use predicted to save 1.2 Mt of wood equivalent each year (Sinha, 1992).

Methanol and ethanol are also proposed as cooking-fuel options. These are liquid fuels, made from wood or crops such as sugarcane and cassava, but the short supply of these crops makes the process expensive (CSE, 1985).

OFF-SITE ENVIRONMENTAL EFFECTS FROM BIOMASS HARVESTING AND EROSION

Harvesting biomass and thereby intensifying erosion and water runoff causes several off-site environmental problems. For instance, water runoff in the United States is "delivering approximately 4 billion t/year of sediment to waterways in the 48 contiguous states" (Pimentel, 1995). About 60% of these sediments come from fertile agricultural lands (Highfill and Kimberlin, 1977). These off-site effects cost an estimated $6 billion annually in the United States (Clark, 1985). Dredging several million cubic meters of sediments from U.S. rivers, harbors, and reservoirs is costly. An estimated 10%–25% of new reservoir storage capacity in the United States is built solely to store sediments (Clark, 1985). These problems are universal. For example, in India, the cost associated with low water flows and heavy siltation that have reduced the storage capacity of reservoirs was estimated to be about $427 million per year in 1980 (Myers, 1986b).

Soil sediments, particularly those containing pesticides and fertilizer nutrients, that are carried into rivers, lakes, and reservoirs from agricultural and forest lands adversely affect fish production (USDI, 1982). Sediments interfere with fish spawning, increase predation on fish, and frequently destroy fish food (NAS, 1982).

These destructive effects reach into estuarines, coastal fisheries, and coral reefs (Alexander, 1979; Day and Grindley, 1981). In the United States, the diverse effects of soil erosion on fish and other wildlife, as well as on water-storage facilities and waterway navigation, are estimated to cost $4.1 billion each year (Clark, 1985).

CONCLUSION

Reaching a sound balance between biomass-food and biomass-fuel production would bring additional economic benefits, despite the fact that food is given higher priority by society and has higher price values than biomass fuels. When governments subsidize biomass fuel production—as in Brazil and the United States with ethanol programs based on sugarcane and corn grain, respectively—a few producers may make enormous profits. In Brazil, revenues to sugarcane growers increased 200% with the ethanol program (Nastari, 1983). However, the heavy subsidization of biomass fuel tends to give higher priority to biomass fuel rather than food. The result is often reduced food production and higher food prices. Food shortages and high food prices have many negative effects for society, including poor child nutrition. The poor commonly suffer the most when food costs rise. Without sound soil and water conservation policies, subsidizing biomass fuel can result in poorer management of important soil, water, and biological resources (ERAB, 1981).

Other societal effects from biomass fuels programs include reducing the standard of living of the labor force, as happened in Brazil (Pluijm, 1982; OECD, 1984). In addition, the occupational risks in the labor force increase when biomass fuels are given priority over fossil fuels (Pimentel et al., 1984).

REFERENCES

AAC. 1980. *Agricultural Almanac of China* (*Zhonggue Nongye Nianjian*). Beijing: Agricultural Press.

Alexander, W.J.R. 1979. Sedimentation of estuaries: Causes, effects and remedies. Fourth (South African) National Oceanography Symposium. Cape Town, July. Council for Scientific and Industrial Research, Pretoria.

Allen, J.A. 1986. Fuelwood policies for Swazi nation land: Farm and community approaches for fuelwood production. M.S. thesis, Cornell University, Ithaca, NY.

Arledge, J.E. 1980. Soil conservation at work: Guatemala's small farmer project. *Journal of Soil and Water Conservation* 35: 187–189.

Bailie, R.C. 1976. *Technical and Economic Assessment of Methods for Direct Conversion of Agricultural Residue to Energy*. Morgantown, WV: West Virginia University.

Baker, J.B. 1973. Intensive cultural practices increase growth of juvenile slash pine in Florida Sandhills. *Forest Science* 19: 197–202.

Banwell, P.S. and R.C. Harriss. 1992. Enhancing biomass energy use in Kenya. *Natural Resources Forum* 16(4): 298–304.

Boddey, R.M. 1995. Biological nitrogen fixation in sugar cane: A key to energetically viable biofuel production. *Critical Reviews in Plant Sciences* 14: 263–279.

Bogach, V.S. 1985. *Wood as Fuel*. New York: Praeger Publishers.

Bolline, A. 1982. Etude et prevision de l'erosion des sols limoneux cultives en Moyenne Belgique. These presentee pour l'obtention du grade de Docteur en Sciences Geographiques, Universite de Liege. Cited in Richter, G. 1983.

Brabben, T.E. 1981. Use of turbidity monitors to assess sediment yield in East Java, Indonesia. In *Erosion and Sediment Transport Measurement*, pp. 105–113. International Association of Hydrology Sciences Publication No. 133.

Brown, L.R. and E.C. Wolf. 1984. Soil erosion: quiet crisis in the world economy. Worldwatch Paper No. 60. Washington, D.C.: Worldwatch Institute.

Bureau of Labor Statistics (BLS). 1978. Chartbook on occupational injuries and illnesses in 1976. Report 535. U.S. Department of Labor, Washington, D.C.

Bureau of Labor Statistics (BLS). 1979. Occupational injuries and illnesses in 1977, summary. Report 561. U.S. Department of Labor, Washington, D.C.

Bureau of Labor Statistics (BLS). 1980. Occupational injuries and illnesses in the United States by industry, 1978. Bulletin 2078. U.S. Department of Labor, Washington, D.C.

Bureau of Labor Statistics (BLS). 1981. Occupational injuries and illnesses in the United States by industry, 1979. Summary. Bulletin 2097. Washington, D.C.: U.S. Department of Labor.

Burnett, E. and E.C. Fisher. 1954. The effect of conservation practices on runoff, available soil moisture and cotton yield. *Proceedings of the Soil Science Society of America* 18: 216–218.

Calle, F.R. and D.O. Hall. 1987. Brazilian alcohol: Food versus fuel. Unpublished manuscript.

Centre for Science and Environment (CSE). 1982. *The State of India's Environment 1982. A Citizen's Report.* New Delhi: CSE.

Centre for Science and Environment (CSE). 1985. *The State of India's Environment 1984–85. The Second Citizens' Report.* New Delhi: CSE.

Chapman, D. 1983. *Energy Resources and Energy Corporations.* Ithaca, NY: Cornell University Press.

Chapman, D. and Barker, R. 1987. Resource depletion, agricultural research, and development. Paper prepared for U.S. National Academy of Sciences–Czechoslovak Academy of Sciences Workshop on Agricultural Development and Environmental Research, April 6–16, Ceske Budejovice, Czechoslovakia.

Chatterji, M. 1981. Energy and environment in the developing countries: An overall perspective and plans for action. In M. Chatterji (ed.), *Energy and Environment in Developing Countries*, pp. 3–25. New York: John Wiley & Sons.

Clark, E.H. II. 1985. The off-site costs of soil erosion. *Journal of Soil and Water Conservation* 40: 19–22.

da Silva, J.G., G.E. Serra, J.R. Moreira, et al. 1978. Energy balance for ethyl alcohol production from crops. *Science* 201: 903–906.

Day, J.H. and J.R. Grindley. 1981. The estuarine ecosystem and environmental constraints. In J.H. Day (ed.), *Estuarine Ecology*, pp. 345–372. Rotterdam: A.A. Balkema.

de Melo, F.H. 1986. Brazil and the CGIAR centers: A study of their collaboration in agricultural research. CGIAR Paper No. 9. Washington, D.C.: World Bank.

de Montalembert, M.R. and J. Clement. 1983. Fuelwood supplies in the developing countries. Forestry Paper No. 42. Rome: Food and Agriculture Organization.

Department of Science and Technology (DST). 1980. Report of the Committee for Recommending Legislative Measures and Administrative Machinery for Ensuring Environmental Protection. Government of India: DST.

Desai, I.D., G. Tavares, D. de Oliveira, et al. 1980. Food habits and nutritional status of agricultural migrant workers in southern Brazil. *American Journal of Clinical Nutrition* 33: 702–714.

Dickerson, B.P. 1976. Soil compaction after tree-length skidding in northern Mississippi. *Soil Science Society of America Journal* 40: 965–966.

Dils, R.E. 1953. Influence of forest cutting and mountain farming on some vegetation, surface soil, and surface runoff characteristics. USDA Forest Station Paper No. 24. Southeastern Forest Experiment Station.

Dissmeyer, G.E. 1976. Erosion and sediment from forest land uses, management practices and disturbances in the southeastern United States. In *Proceedings of the Third Federal Interagency Sedimentation Conference*, March 22–25, pp. 1140–1141, 148. Denver, CO: Sedimentation Committee, Water Resources Council.

DOE. 1980. *Health Effects of Residential Wood Combustion: Survey of Knowledge and Research*. Washington, D.C.: Department of Energy, Technology Assessments Division.

DOE. 1981. Wood Combustion: State of Knowledge Survey of Environmental, Health and Safety Aspects. Report No. DOE/EY/10450–74. Baltimore: Mueller Associates Inc.

DOE. 1983. Energy Projections to the Year 2010. Office of Policy, Planning, and Analysis, Washington, D.C.: U.S. Department of Energy.

Dunkerley, J. and W. Ramsay. 1983. Analysis of Energy Prospects and Problems of Developing Countries. Report to AID Bureau for Program and Policy Coordination. Washington, D.C.: Resources for the Future.

El-Swaify, S.A., E.W. Dangler, and C.L. Armstrong. 1982. Soil Erosion by Water in the Tropics. Resource Extension Series 024. Honolulu, HI: College of Tropical Agriculture and Human Resources, University of Hawaii, Honolulu.

Energy Research Advisory Board (ERAB). 1980. *Gasohol*. Washington, D.C.: ERAB, U.S. Department of Energy.

Energy Research Advisory Board (ERAB). 1981. *Biomass Energy*. Washington, D.C.: ERAB, U.S. Department of Energy.

Finn, D. 1983. Land use and abuse in the East African region. *Ambio* 12: 296–301.

Flaim, S. and D. Urban. 1980. The Costs of Using Crop Residues in Direct Applications. SERI TR 353–513. Golden, CO: Solar Energy Research Institute.

Food and Agriculture Organization (FAO). 1983a. *1981 Production Yearbook of Forest Products*. Rome: Food and Agriculture Organization of the United Nations.

Food and Agriculture Organization (FAO). 1983b. *Country Tables. Basic Data on the Agricultural Sector*. Rome: Food and Agriculture Organization. Microfiche 833041.

Food and Agriculture Organization (FAO). 1984. *Production Yearbook*, Vol. 38. Rome: Food and Agriculture Organization.

Froelich, H.A. 1978. Soil compaction from low ground-pressure, torsion-suspension logging vehicles on three forest soils. Forestry Research Laboratory. Research Paper 36, Oregon State University, School of Forestry, Corvallis, OR.

Froelich, H.A. 1979. Soil compaction from logging equipment: Effects on growth of young ponderosa pine. *Journal of Soil and Water Conservation* 34: 276–278.

Ghirardi, A.G. 1983. Alcohol fuels from biomass in Brazil: A comparative assessment of methanol vs. ethanol. Ph.D. Dissertation, University of California, Berkeley.

Government of India (GI). 1979. *Report of the Working Group on Energy Policy*. New Delhi: Government of India, Planning Commission.

Hall, D.O. 1985. Biomass: Fuel versus food, a world problem? In D.O. Hall, N. Myers, and N.S. Margaris (eds.), *Economics of Ecosystems Management*, pp. 207–226. Dordrecht, the Netherlands: Junk Publishers.

Hall, D.O., N. Myers, and N.S. Margaris (eds.). 1985. *Economics of Ecosystems Management*. Dordrecht, the Netherlands: Junk Publishers.

Hall, D.O. and P.J. de Groot. 1987. Introduction: The biomass framework. In D.O. Hall and R.P. Overend (eds.), *Biomass*, pp. 3–24. Chichester: John Wiley & Son.

Harrold, L.L., G.B. Triplett, Jr., and R.E. Youker. 1967. Watershed tests of no-tillage corn. *Journal of Soil and Water Conservation* 22(3): 98–100.

Hempel, L. 1951. Über Kartierungsmethoden von Bodenerosion durch Wasser. Neves Arch. Niedersachsen 26, 590–598. In D. Zachar, *Soil Erosion. Developments in Soil Science* 10. Amsterdam: Elsevier Scientific, 1982.

Hempel, L. 1954. Beispiele von Bodenerosionkarten im Niedersächsischen Bergland sowie Bemerkungen über Berücksichtigung der Erosionsschaden bei der Bodenschützung. Neves Arch. Niedersachsen 4–6, 140–143. In D. Zachar, *Soil Erosion. Developments in Soil Science* 10. Amsterdam: Elsevier Scientific, 1982.

Hendrickson, B.H., A.P. Barnett, J.R. Carreker, et al. 1963. Runoff and erosion control studies on Cecil soil in the southern Piedmont. U.S. Department of Agriculture Technical Bulletin No. 1281.

Hewlett, J.D. 1979. Forest water quality. An experiment in harvesting and regenerating Piedmont forest, Georgia Forest Research Paper, School of Forest Resources, University of Georgia, Athens.

Highfill, R. and L. Kimberlin. 1977. Current soil erosion and sediment control technology for rural and urban lands. In *Proceedings of a National Symposium on Soil Erosion and Sedimentation by Water*, pp. 14–22. Chicago: American Society of Agricultural Engineers.

Hornbeck, J.W., G.E. Likens, R.S. Pierce, et al. 1973. Strip cutting as a means of protecting site and streamflow quality when clearcutting northern hardwoods. In B. Bernier and C.H. Winget (eds.), *Forest Soils and Forest Land Management*, pp. 209–225. Procedures of the Fourth North American Soils Conference. Quebec, Canada: Laval University Press.

Hosier, R. 1985. Energy Use in Rural Kenya: Household Demand and Rural Transformation. Beijer Institute, Royal Swedish Academy of Sciences, Scandinavian Institute of African Studies. Energy, Environment and Development in Africa No. 7, OAE. Stockholm, Uppsala.

Jewell, W.J. and G.R. Morris. 1974. The economic and technical feasibility of methane generation from agricultural waste. In R.J. Catania (ed.), *Uses of Agricultural Wastes: Food, Fuel, Fertilizer*, pp. 132–164. Regina, Canada: University of Regina.

Jewell, W.J., H.R. Davis, W.W. Gunkel, et al. 1977. Bioconversion of Agricultural Wastes for Pollution Control and Energy Conservation. Division of Solar Energy, ERDA. Springfield, VA: National Technical Information Service.

Khoshoo, T.N. 1986. *Environmental Priorities in India and Sustainable Development.* New Delhi: Indian Science Congress Association.

Kidd, C. and D. Pimentel (eds.) 1992. *Integrated Resource Management: Agroforestry for Development.* San Diego, CA: Academic Press.

Klock, G.O. 1982. Some soil erosion effects on forest soil productivity. In *Determinants of Soil Loss Tolerance*, pp. 53–66. American Society of Agronomy Special Publication No. 45, Soil Science Society of America. Madison, WI: American Society of Agronomy.

Kuby, W., R. Markoja, and S. Nackford. 1984. *Testing and Evaluation of On-Farm Alcohol Production Facilities.* Cincinnati, OH: Acurex Corporation, Industrial Environmental Research Laboratory, Office of Research and Development, U.S. EPA.

Kurian, G.T. 1995. *Encyclopedia of the Third World.* Fourth edition. New York: Facts on File, Inc.

Lamb, R. and S. Milas. 1983. Soil erosion, real cause of Ethiopian famine. *Environmental Conservation* 10: 157–159.

Lal, R. 1983. Erosion-caused productivity decline in soils of the humid tropics. *Soil Taxonomy News* 5: 4–5, 18.

La Rovere, E.L. 1985. A south-south assault on the food/energy problem. *Ceres* 18(1): 25–28.

Lee, L.K. 1984. Land use and soil loss: A 1982 update. *Journal of Soil and Water Conservation* 39: 226–228.

Lewis, C.W. 1976. Fuel production from biomass. Report No. 7, Systems Analysis Research Unit, Energy Studies Unit. University of Strathclyde, Glasgow.

Mannering, J.V. 1984. Conservation tillage to maintain soil productivity and improve water quality. Agronomy Guide (Tillage) AY–222. Cooperative Extension Service, Purdue University, West Lafayette, IN.

Meade, G.P. and J.C.P. Chen. 1977. *Cane Sugar Handbook.* New York: John Wiley & Sons.

Megahan, W. F. 1972. Logging, erosion, sedimentation—are they dirty words? *Journal of Forestry* 70: 403–407.

Megahan, W.F. 1975. Sedimentation in relation to logging activities in the mountains of central Idaho. In *Present and Prospective Technology for Predicting Sediment Yields and Sources*, pp. 74–82. Proceedings of Sediment-Yield Workshop, USDA, Sedimentation Laboratory, Oxford, Mississippi, November 28–30, 1972. USDA Agricultural Research Service, ARS-S–40.

Ministerio de Minas e Energia (MME). 1987. Ava liacao do Programa Nacional do A'lcool. Comissao Nacional de Energia, Ministe'rio de Minas e Energia, Brasilia.

Mishra, R.K. (ed.) 1986. *India Toward the 1990s.* New Delhi: Patriot Publishers.

Molofsky, J., C.A.S. Hall, and N. Myers. 1986. *A Comparison of Tropical Forest Surveys.* Washington, D.C.: U.S. Department of Energy, CO_2 Research Division.

Morris, S.C. 1981. *Health Effects of Residential Wood Fuel Use.* Upton, NY: Brookhaven National Laboratory.

Myers, N. 1986a. Forestland farming in western Amazonia: Stable and sustainable. *Forest Ecology and Management* 15: 81–93.

Myers, N. 1986b. Environmental repercussions of deforestation in the Himalayas. *Journal of World Forest Resource Management* 2: 63–72.

Narayana, D.V.V. and R. Babu. 1983. Estimation of soil erosion in India. *Journal of Irrigation and Drainage Engineering* 109: 419–434.

Nastari, P.M. 1983. The role of sugar cane in Brazil's history and economy. Ph.D. thesis, Iowa State University, Ames, IA.

National Academy of Sciences (NAS). 1980. *Firewood Crops: Shrubs and Tree Species for Energy Production.* Washington, D.C.: National Academy Press.

National Academy of Sciences (NAS). 1982. *Impact of Emerging Agricultural Trends on Fish and Wildlife Habitat.* Washington, D.C.: National Academy Press.

Office of Technology Assessment (OTA). 1980. *Energy from Biological Processes*, Vols. 1 and 2. Washington, D.C.: U.S. Congress Office of Technology Assessment.

Office of Technology Assessment (OTA). 1984. *Technologies to Sustain Tropical Forest Resources.* OTA-F–214. Washington, D.C.: U.S. Congress Office of Technology Assessment.

O'Keefe, P. 1983. The causes, consequences and remedies of soil erosion in Kenya. *Ambio* 12: 302–305.

O'Keefe, P. and P. Raskin. 1985. Fuelwood in Kenya: Crisis and opportunity. *Ambio* 14: 220–224.

O'Keefe, P., P. Raskin, and S. Bernow (eds.). 1984. *Energy and Development in Kenya: Opportunities and Constraints.* Stockholm, Uppsala: Beijer Institute, Royal Swedish Academy of Sciences, Scandinavian Institute of African Studies. Energy, Environment and Development in Africa.

Organization for Economic Cooperation and Development (OECD). 1984. *Biomass for Energy: Economic and Policy Issues.* Paris: OECD.

Ortmaier, E. 1981. The production of ethanol from sugarcane: Brazil's experiment for a partial solution to the energy problem. *Quarterly Journal of International Agriculture* 20: 265–278.

Osuji, G.E. 1984. The gullies of Imo. *Journal of Soil and Water Conservation* 39: 246–247.

Patric, J.H. 1976. Soil erosion in the eastern forest. *Journal of Forestry* 74: 671–677.

Patric, J.H. 1980. Effect of wood products harvest on forest soil and water relations. *Journal of Environmental Quality* 9: 73–80.

Patric, J.H., J.O. Evans, and J.D. Helvey. 1984. Summary of sediment yield data from forested land in the United States. *Journal of Forestry* 82: 101–104.

Pereira, A. 1983. Employment implications of ethanol production in Brazil. *International Labour Review* 122: 111–127.

Pimentel, D. (ed.). 1980. *Handbook of Energy Utilization in Agriculture.* Boca Raton, FL: CRC Press.

Pimentel, D. 1991. Ethanol fuels: energy security, economics, and the environment. *Journal of Agricultural and Environmental Ethics* 4: 1–13.

Pimentel, D. 1995. Biomass fuel and environmental sustainability in agriculture. In T.B. Mepham, G.A. Tucker, and J. Wiseman (eds.), *Issues in Agricultural Bioethics*, pp. 215–228. Nottingham, UK: Nottingham University Press.

Pimentel, D. and J. Krummel. 1987. Biomass energy and soil erosion: Assessment of resource costs. *Biomass* 14: 15–38.

Pimentel, D., A.F. Warneke, W.S. Teel, et al. 1988. Food versus biomass fuel: Socioeconomic and environmental impacts in the United States, Brazil, India, and Kenya. *Advances in Food Research* 32: 185–238.

Pimentel, D., C. Fried, L. Olson, et al. 1983a. Biomass energy: Environmental and social costs. Environmental Biology Report 83–2, Cornell University, Ithaca, NY.

Pimentel, D., C. Fried, L. Olson, et al. 1984. Environmental and social costs of biomass energy. *BioScience* 34: 89–94.

Pimentel, D., D. Nafus, W. Vergara, et al. 1978. Biological solar energy conversion and U.S. energy policy. *BioScience* 28: 376–382.

Pimentel, D., D. Wen, S. Eigenbrode, et al. 1986a. Deforestation: Interdependency of fuelwood and agriculture. *Oikos* 46: 404–412.

Pimentel, D., J. Allen, A. Beers, et al. 1987. World agriculture and soil erosion. *BioScience* 37: 277–283.

Pimentel, D., L. McLaughlin, A. Zepp, et al. 1991. Environmental and economic impacts of reducing U.S. agricultural pesticide use. In D. Pimentel (ed.), *Handbook of Pest Management in Agriculture*, Vol. I, pp. 679–718. Boca Raton, FL: CRC Press.

Pimentel, D., L.E. Hurd, A.C. Bellotti, et al. 1973. Food production and the energy crisis. *Science* 182: 443–449.

Pimentel, D., M. Herdendorf, S. Eisenfeld, et al. 1994. Achieving a secure energy future: Environmental and economic issues. *Ecological Economics* 9(3): 201–219.

Pimentel, D., M.A. Moran, S. Fast, et al. 1981. Biomass energy from crop and forest residues. *Science* 212: 1110–1115.

Pimentel, D., S. Fast, D. Gallahan, et al. 1983b. Environmental risks of utilizing crop and forest residues for biomass energy. In *Proceedings of the Intersociety Energy Conversion Engineering Conference*, pp. 580–585. Orlando, FL, August 21–26, 1983.

Pimentel, D., W. Dazhong, S. Eigenbrode, et al. 1986b. Deforestation: Interdependency of fuelwood and agriculture. *Oikos* 46: 404–412.

Pluijm, T. van der. 1982. Energy versus food? Implications of macro-economic adjustments on land-use patterns: The ethanol programme in Brazil. *Boletin de Estudios Latinoamericanos y del Caribe* 33: 85–106.

Population Reference Bureau (PRB). 1977. *1977 World Population Data Sheet.* Washington, D.C.: PRB, Inc.

Population Reference Bureau (PRB). 1993. *1993 World Population Data Sheet.* Washington, D.C.: PRB, Inc.

Population Reference Bureau (PRB). 2006. *2006 World Population Data Sheet.* Washington, D.C.: PRB, Inc.

Power, J.F. and R.I. Papendick. 1985. Organic sources of nutrients. In O. P. Engelstad (ed.), *Fertilizer Technology and Use*, pp. 503–520. Madison, WI: Soil Science Society of America.

Randrianarijaona, P. 1983. The erosion of Madagascar. *Ambio* 12: 308–311.

Ricaud, R. 1980. Energy input and output for sugarcane in Louisiana. In D. Pimentel (ed.), *Handbook of Energy Utilization in Agriculture*, pp. 135–136. Boca Raton, FL: CRC Press.

Rice, R.M., J.S. Rothacher, and W.F. Megahan. 1972. Erosional consequences of timber harvesting: An appraisal. In *Proceedings of the National Symposium on Watersheds in Transition*, pp. 321–329. Fort Collins, CO: American Water Resources Association.

Richter, G. 1983. Aspects and problems of soil erosion hazard in the EEC countries. In A.G. Pendergast (ed.), *CEC Soil Erosion and Conservation Symposium Proceedings*, pp. 9–18. Florence, Italy: Commission of the European Communities.

Sanchez-Sierra, G. and A. Umana-Quesada. 1984. Quantitative analysis of the role of biomass within energy consumption in Latin America. *Biomass* 4: 21–41.

Sauer, E.L. and H.C.M. Case. 1954. Soil conservation pays off. Results of ten years of conservation farming in Illinois. University of Illinois Agricultural Experiment Station Bulletin 575.

Sharma, A. 1987. *Resources and Human Well-Being: Inputs from Science and Technology.* Calcutta: Indian Science Congress Association.

Silva, J.R.C., M.A. Coelho, E.G.S. Moreira, et al. 1985. Efeitos da erosao na produtividade de dois solos da classe la tossolo vermelho-amarelo. *Ciencia Agronomica Fortaleza* 16: 55–63.

Sinha, C.S. 1992. Renewable energy programmes in India: A brief review of experience and prospects. *Natural Resources Forum* 16: 305–314.

Slesser, M. and C. Lewis. 1979. *Biological Energy Resources.* New York: Halsted Press.

Smith, D.D. 1946. The effect of contour planting on crop yield and erosion losses in Missouri. *Journal of the American Society of Agronomy* 38: 810–819.

Sourie, J.C. and L. Killen. 1986. *Biomass: Recent Economic Studies.* London and New York: Elsevier Applied Science Publishers.

Stafford, D.A. 1983. Methane from farm wastes and energy recovery. In D.L. Wise (ed.), *Fuel Gas Developments*, pp. 1–17. Boca Raton, FL: CRC Press.

Stuckey, D. and C. Juma. 1985. Power alcohol in Kenya and Zimbabwe: A case study in the transfer of a renewable energy technology. UNCTAD/TT/61, UNCTAD secretariat.

Successful Farming (SF). 1983. 19,000 lb of milk and 850 kwh of electricity, pp. D2–4, December.

Swank, W.T. and J.E. Douglass. 1977. Nutrient budgets for undisturbed and manipulated hardwood forest ecosystems in the mountains of North Carolina. In D.L. Correll (ed.), *Watershed Research in Eastern North America. A Workshop to Compare Results*, pp. 343–363. Vol. I, February 28–March 3. Edgewater, MD: Smithsonian Institution, Chesapeake Bay Center for Environmental Studies.

Swanston, D.N. and C.T. Dyrness. 1973. Managing steep land. *Journal of Forestry* 71: 264–269.

Teel, W. 1984. *A Pocket Directory of Trees and Seeds in Kenya*. Nairobi: KENGO.

United Nations (UN). 1976. *Statistical Yearbook*, Vol. 30. New York: United Nations.

United Nations (UN). 1982. *Statistical Yearbook, 1980*, Vol. 33. New York: United Nations.

United Nations (UN). 1986. *Energy Balance and Electricity Profiles 1984.* New York: United Nations.

U.S. Bureau of the Census (USBC). 1992. *Current Population Reports.* January edition. Washington, D.C.: USBC.

U.S. Department of Agriculture (USDA). 1985. *Agricultural Statistics 1985.* Washington, D.C.: U.S. Government Printing Office.

U.S. Department of Agriculture (USDA). 1991a. *Agricultural Statistics 1991.* Washington, D.C.: Government Printing Office.

U.S. Department of Agriculture (USDA). 1991b. Agricultural Resources: Cropland, Water, and Conservation Situation and Outlook Report. Economic Research Service, AR–23. Washington, D.C.: U.S. Department of Agriculture.

U.S. Department of Agriculture (USDA). 1994. Summary Report 1992 National Resources Inventory. Washington, D.C.: Soil Conservation Service, USDA.

USDA-ARS and EPA-ORD. 1976. Control of Water Pollution from Cropland. EPA Report No. EPA–600/2–75–0266, ARS Report No. ARS-H–5–2. 2 vols. Washington, D.C.: U.S. Government Printing Office.

U.S. Department of the Interior (USDI). 1982. Manual of stream channelization impacts on fish and wildlife. U.S. Department of Interior, Fish and Wildlife Service. Biological Services Program. July 1982.

U.S. Forest Service (USFS). 1977. Generalized erosion and sediment rates for disturbed and undisturbed forest land in the Northeast. U.S. Forest Service, USDA.

Vergara, W., F. Welsch, and D. Serviansky. 1977. Utilization of food processing wastes. Unpublished data. Department of Food Science, Cornell University, Ithaca, NY.

Wiggins, S.L. 1981. The economics of soil conservation in the Acelhuate River Basin, El Salvador. In R.P.C. Morgan (ed.), *Soil Conservation: Problems and Prospects*, pp. 399–415. Chichester: John Wiley & Sons.

Wijewardene, R. and P. Waidyanatha. 1984. Systems, techniques and tools. Conservation farming for small farmers in the humid tropics. Department of Agriculture, Sri Lanka and the Commonwealth Consultative Group on Agriculture for the Asia-Pacific Region.

World Development Report. 1995. Published for the World Bank. New York: Oxford University Press.

World Resources Institute (WRI). 1984. *World Resources 1984–1985*. Washington, D.C.: World Resources Institute.

World Resources Institute (WRI). 1992. *World Resources 1992–1993*. New York: Oxford University Press.

World Resources Institute (WRI). 1994. *World Resources 1994–1995*. Washington, D.C.: World Resources Institute.

World Tables. 1995. Published for the World Bank. Baltimore: Johns Hopkins University Press.

Yeager, R. and N.N. Miller. 1986. *Wildlife, Wild Death: Land Use and Survival in Eastern Africa*. Albany, NY: State University of New York Press.

Yoho, N.S. 1980. Forest management and sediment production in the South—a review. *Southern Journal of Applied Forestry* 4: 27–35.

Zachar, D. 1982. *Soil Erosion*. New York: Elsevier Scientific.

21 Ethanol Production Using Corn, Switchgrass, and Wood; Biodiesel Production Using Soybean and Sunflower*

David Pimentel and Tad W. Patzek

The United States desperately needs a liquid fuel replacement for oil in the future. The use of oil is projected to peak about 2007 and the supply is then projected to be extremely limited in 40–50 years (Youngquist and Duncan, 2003; Pimentel et al., 2004a). Alternative liquid fuels from various sources have been sought for many years. Two panel studies by the U.S. Department of Energy (USDOE) dealing with ethanol production using corn and liquid fuels from biomass energy report a negative energy return (ERAB, 1980, 1981). These reports were reviewed by 26 expert U.S. scientists independent of the USDOE; the findings indicated that the conversion of corn into ethanol energy was negative and these findings were unanimously approved. Numerous other investigations have confirmed these findings over the past two decades.

A review of the reports that indicate that corn ethanol production provides a positive return indicates that many inputs were omitted (Pimentel, 2003). It is disappointing that many of the inputs were omitted because this misleads U.S. policy makers and the public.

Ethanol production using corn, switchgrass, and wood, and biodiesel production using soybeans and sunflower, will be investigated in this chapter.

ETHANOL PRODUCTION USING CORN

Shapouri et al. (2002, 2004) of the USDA claim that ethanol production provides a net energy return. In addition, some large corporations, including Archer, Daniels, and Midland (McCain, 2003), support the production of ethanol using corn and are making huge profits from ethanol production, which is subsidized by federal and state governments. Some politicians also support the production of corn ethanol

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based on their mistaken belief that ethanol production provides large benefits for farmers, while in fact farmer profits are minimal. In contrast to the USDA, numerous scientific studies have concluded that ethanol production does not provide a net energy balance, that ethanol is not a renewable energy source, is not an economical fuel, and its production and use contribute to air, water, and soil pollution and global warming (Ho, 1989; Citizens for Tax Justice, 1997; Giampietro et al., 1997; Pimentel, 1998, 2001, 2003; Youngquist, 1997; NPRA, 2002; Croysdale, 2001; CalGasoline, 2002; Lieberman, 2002; Hodge, 2002, 2003; Ferguson, 2003, 2004; Patzek, 2004). Growing large amounts of corn necessary for ethanol production occupies cropland suitable for food production and raises serious ethical issues (Pimentel, 1991, 2003; Pimentel and Pimentel, 1996).

Shapouri et al. (2002, 2004) studies concerning the benefits of ethanol production are incomplete because they omit some of the energy inputs in the ethanol production system. The objective of this analysis is to update and assess all the recognized inputs that operate in the entire ethanol production system. These inputs include the direct costs in terms of energy and dollars for producing the corn feedstock as well as for the fermentation/distillation process. Additional costs to the consumer include federal and state subsidies, plus costs associated with environmental pollution and degradation that occur during the entire production system. Ethanol production in the United States does not benefit the nation's energy security, its agriculture, the economy, or the environment. Also, ethical questions are raised by diverting land and precious food into fuel and actually adding a net amount of pollution to the environment.

ENERGY BALANCE

The conversion of corn and other food/feed crops into ethanol by fermentation is a well-known and established technology. The ethanol yield from a large production plant is about 1 L from 2.69 kg of corn grain (Pimentel, 2001).

The production of corn in the United States requires a significant energy and dollar investment (Table 21.1). For example, to produce an average corn yield of 8655 kg/ha of corn using average production technology requires the expenditure

TABLE 21.1

Energy Inputs and Costs of Corn Production per Hectare in the United States

Inputs	Quantity	kcal × 1000	Costs ($)
Labor	11.4 h[a]	462[b]	148.20[c]
Machinery	55 kg[d]	1018[e]	103.21[f]
Diesel	88 L[g]	1003[h]	34.76
Gasoline	40 L[i]	405[j]	20.80
Nitrogen	153 kg[k]	2448[l]	94.86[m]
Phosphorus	65 kg[k]	270[n]	40.30[o]
Potassium	77 kg[k]	251[p]	23.87[q]
Lime	1120 kg[r]	315[s]	11.00

TABLE 21.1 (continued)

Energy Inputs and Costs of Corn Production per Hectare in the United States

Inputs	Quantity	kcal × 1000	Costs ($)
Seeds	21 kg[d]	520[t]	74.81[u]
Irrigation	8.1 cm[v]	320[w]	123.00[x]
Herbicides	6.2 kg[y]	620[z]	124.00
Insecticides	2.8 kg[k]	280[z]	56.00
Electricity	13.2 kWh[aa]	34[bb]	0.92
Transport	204 kg[cc]	169[dd]	61.20
Total		8115	916.93
Corn yield 8655 kg/ha[ee]		31,158	kcal input:output 1:3.84

[a] NASS (1999).

[b] It is assumed that a person works 2000 h/year and utilizes an average of 8000 L of oil equivalents per year.

[c] It is assumed that labor is paid $13/h.

[d] Pimentel and Pimentel (1996).

[e] Prorated per hectare and 10-year life of the machinery. Tractors weigh from 6 to 7 tons and harvesters 8 to 10 tons, plus plows, sprayers, and other equipment.

[f] Hoffman et al. (1994).

[g] Wilcke and Chaplin (2000).

[h] Input 11,400 kcal/L.

[i] Estimated.

[j] Input 10,125 kcal/L.

[k] USDA (2002).

[l] Patzek (2004).

[m] Cost 62¢/kg.

[n] Input 4154 kcal/kg.

[o] Cost 62$/kg.

[p] Input 3260 kcal/kg.

[q] Cost 31¢/kg.

[r] Brees (2004).

[s] Input 281 kcal/kg.

[t] Pimentel (1980).

[u] USDA (1997b).

[v] USDA (1997a).

[w] Batty and Keller (1980).

[x] Irrigation for 100 cm of water per hectare costs $1000 (Larsen et al., 2002).

[y] Larson and Cardwell (1999).

[z] Input 100,000 kcal/kg of herbicide and insecticide.

[aa] USDA (1991).

[bb] Input 860 kcal per kWh and requires 3 kWh thermal energy to produce 1 kWh electricity.

[cc] Goods transported include machinery, fuels, and seeds that were shipped an estimated 1000 km.

[dd] Input 0.83 kcal per kg per km transported.

[ee] USDA (2003a).

of about 8.1 million kcal for the large number of inputs listed in Table 21.1 (about 271 gal of gasoline equivalents/ha). The production costs are about $917/ha for the 8655 kg or approximately 11¢/kg of corn produced. To produce a liter of ethanol requires 29% more fossil energy than is produced as ethanol and costs 42¢/L ($1.59/gal) (Table 21.2). The corn feedstock alone requires nearly 50% of the energy input.

Full irrigation (when there is little or no rainfall) requires about 100 cm of water per growing season. Only approximately 15% of U.S. corn production currently is irrigated (USDA, 1997a). Of course not all of this requires full irrigation, so a mean value is used. The mean irrigation for all land growing corn grain is 8.1 cm/ha during the growing season. As a mean value, water is pumped from a depth of 100 m (USDA, 1997a). On this basis, the mean energy input associated with irrigation is 320,000 kcal/ha (Table 21.1).

The average costs in terms of energy and dollars for a large (245–285 million L/year), modern ethanol plant are listed in Table 21.2. Note the largest energy inputs are for the corn feedstock, the steam energy, and electricity used in the fermentation/distillation process. The total energy input to produce a liter of ethanol is 6597 kcal (Table 21.2). However, a liter of ethanol has an energy value of only 5130 kcal. Thus, there is a net energy loss of 1467 kcal of ethanol produced. Not included in this analysis was the distribution energy to transport the ethanol. DOE (2002) estimates this to be 2¢/L or approximately more than 331 kcal/L of ethanol.

In the fermentation/distillation process, the corn is finely ground and approximately 15 L of water are added per 2.69 kg of ground corn. After fermentation, to obtain a gallon of 95% pure ethanol from the 8% ethanol and 92% water mixture, the 1 L of ethanol must come from the approximately 13 L of the ethanol/water mixture. A total of about 13 L of wastewater must be removed per liter of ethanol produced and this sewage effluent has to be disposed of at both an energy and economic cost.

Although ethanol boils at about 78°C while water boils at 100°C, the ethanol is not extracted from the water in just one distillation process. Instead, about three distillations are required to obtain the 95% pure ethanol (Maiorella, 1985; Wereko-Brobby and Hagan, 1996; S. Lamberson, personal communication, Cornell University, 2000). To be mixed with gasoline, the 95% ethanol must be further processed and more water removed requiring additional fossil energy inputs to achieve 99.5% pure ethanol (Table 21.2). The entire distillation accounts for the large quantities of fossil energy required in the fermentation/distillation process (Table 21.2). Note, in this analysis all the added energy inputs for the fermentation/distillation process total $422.21, including the apportioned energy costs of the stainless steel tanks and other industrial materials (Table 21.2).

About 50% of the cost of producing ethanol (42¢/L) in a large-production plant is for the corn feedstock itself (28¢/L) (Table 21.2). The next largest input is for steam (Table 21.2).

Based on current ethanol production technology and recent oil prices, ethanol still costs substantially more to produce in dollars than it is worth on the market. Clearly, without the more than $3 billion of federal and state government subsidies

TABLE 21.2

Inputs per 1000 L of 99.5% Ethanol Produced from Corn[a]

Inputs	Quantity	kcal × 1000	Costs ($)
Corn grain	2,690 kg[b]	2522[b]	284.25[b]
Corn transport	2,690 kg[b]	322[c]	21.40[d]
Water	40,000 L[e]	90[f]	21.16[g]
Stainless steel	3 kg[h]	12[h]	10.60[d]
Steel	4 kg[h]	12[h]	10.60[d]
Cement	8 kg[h]	8[h]	10.60[d]
Steam	2,546,000 kcal[i]	2546[i]	21.16[j]
Electricity	392 kWh[i]	1011[i]	27.44[k]
95% ethanol to 99.5%	9 kcal/L[l]	9[l]	40.00
Sewage effluent	20 kg BOD[m]	69[n]	6.00
Total		6597	453.21

[a] Output: 1 L of ethanol = 5130 kcal.

[b] Data from Table 21.1.

[c] Calculated for 144-km roundtrip.

[d] Pimentel (2003).

[e] 15 L of water mixed with each kg of grain.

[f] Pimentel et al. (1997).

[g] Pimentel et al. (2004).

[h] Slesser and Lewis (1979).

[i] Illinois Corn (2004).

[j] Calculated based on coal fuel.

[k] 7¢ per kWh.

[l] 95% ethanol converted to 99.5% ethanol for addition to gasoline (T. Patzek, personal communication, University of California, Berkeley, 2004).

[m] 20 kg of BOD per 1000 L of ethanol produced (Kuby et al., 1984).

[n] 4 kWh of energy required to process 1 kg of BOD (Blais et al., 1995).

each year, U.S. ethanol production would be reduced or cease, confirming the basic fact that ethanol production is uneconomical (National Center for Policy Analysis, 2002). Senator McCain reports that including the direct subsidies for ethanol plus the subsidies for corn grain, a liter costs 79¢ ($3/gal) (McCain, 2003). If the production costs of producing a liter of ethanol were added to the tax subsidies, then the total cost for a liter of ethanol would be $1.24. Because of the relatively low energy content of ethanol, 1.6 L of ethanol has the energy equivalent of 1 L of gasoline. Thus, the cost of producing an equivalent amount of ethanol to equal a liter of gasoline is $1.88 ($7.12/gal of gasoline), while the current cost of producing a liter of gasoline is 33¢ (USBC, 2003).

Federal and state subsidies for ethanol production that total more than 79¢/L are mainly paid to large corporations (McCain, 2003). To date, a conservative calculation suggests that corn farmers are receiving a maximum of only an added 2¢ per bushel for their corn or less than $2.80 per acre because of the corn ethanol production system. Some politicians have the mistaken belief that ethanol production provides large benefits for farmers, while in fact the farmer profits are minimal. However, several corporations, like Archer, Daniels, Midland, are making huge profits from ethanol production (McCain, 2003). The costs to the consumer are greater than the $8.4 billion/year used to subsidize ethanol and corn production because producing the required corn feedstock increases corn prices. One estimate is that ethanol production is adding more than $1 billion to the cost of beef production (National Center for Policy Analysis, 2002). Because about 70% of the corn grain is fed to U.S. livestock (USDA, 2003), doubling or tripling ethanol production can be expected to increase corn prices further for beef production and ultimately increase costs to the consumer. Therefore, in addition to paying the $8.4 billion in taxes for ethanol and corn subsidies, consumers are expected to pay significantly higher meat, milk, and egg prices in the market place.

Currently, about 2.81 billion gal of ethanol (10.6 billion L) are being produced in the United States each year (Kansas Ethanol, 2004). The total automotive gasoline delivered in the United States was 500 billion L in 2003 (USCB, 2004). Therefore, 10.6 billion L of ethanol (equivalent to 6.9 billion L of gasoline) provided only 2% of the gasoline utilized by U.S. automobiles each year. To produce the 10.6 billion L of ethanol we use about 3.3 million ha of land. Moreover, significant quantities of energy are needed to sow, fertilize, and harvest the corn feedstock.

The energy and dollar costs of producing ethanol can be offset partially by the by-products produced, like the dry distillers grains (DDG) made from dry-milling. From about 10 kg of corn feedstock, about 3.3 kg of DDG can be harvested that has 27% protein (Stanton, 1999). This DDG has value for feeding cattle that are ruminants, but has only limited value for feeding hogs and chickens. The DDG is generally used as a substitute for soybean feed that has 49% protein (Stanton, 1999). Soybean production for livestock production is more energy efficient than corn production because little or no nitrogen fertilizer is needed for the production of this legume (Pimentel et al., 2002). Only 2.1 kg of 49% soybean protein is required to provide the equivalent of 3.3 kg of DDG. Thus, the credit fossil energy per liter of ethanol produced is about 445 kcal (Pimentel et al., 2002). Factoring this credit in the production of ethanol reduces the negative energy balance for ethanol production from 29% to 20% (Table 21.2). Note that the resulting energy output/input comparison remains negative even with the credits for the DDG by-product. Also note that these energy credits are contrived because no one would actually produce livestock feed from ethanol at great costs in fossil energy and soil depletion (Patzek, 2004).

When considering the advisability of producing ethanol for automobiles, the amount of cropland required to grow sufficient corn to fuel each automobile should be understood. To make ethanol production appear positive, we use Shapouri et al.'s (2002, 2004) suggestion that all natural gas and electricity inputs be ignored and only gasoline and diesel fuel inputs be assessed; then, using Shapouri's input/output data results in an output of 775 gal of ethanol per hectare.

Because of its lower energy content, this ethanol has the same energy as 512 gal of gasoline. An average U.S. automobile travels about 20,000 miles/year and uses about 1000 gal of gasoline per year (USBC, 2003). To replace only a third of this gasoline with ethanol, 0.6 ha of corn must be grown. Currently, 0.5 ha of cropland is required to feed each American. Therefore, even using Shapouri's optimistic data, to feed one automobile with ethanol, substituting only one third of the gasoline used per year, Americans would require more cropland than they need to feed themselves!

Until recently, Brazil had been the largest producer of ethanol in the world. Brazil used sugarcane to produce ethanol and sugarcane is a more efficient feedstock for ethanol production than corn grain (Pimentel and Pimentel, 1996). However, the energy balance was negative and the Brazilian government subsidized the ethanol industry. There the government was selling ethanol to the public for 22¢/L that was costing them 33¢/L to produce for sale (Pimentel, 2003). Because of serious economic problems in Brazil, the government has abandoned directly subsidizing ethanol (Spirits Low, 1999). The ethanol industry is still being subsidized but the consumer is paying this subsidy directly at the pump (Pimentel, 2003).

ENVIRONMENTAL IMPACTS

Some of the economic and energy contributions of the by-products mentioned earlier are negated by the environmental pollution costs associated with ethanol production. These are estimated to be more than 6¢/L of ethanol produced (Pimentel, 2003). U.S. corn production causes more total soil erosion than any other U.S. crop (Pimentel et al., 1995; NAS, 2003). In addition, corn production uses more herbicides and insecticides than any other crop produced in the United States, thereby causing more water pollution than any other crop (NAS, 2003). Further, corn production uses more nitrogen fertilizer than any crop produced and therefore is a major contributor to ground water and river water pollution (NAS, 2003). In some Western irrigated corn acreage, for instance, in some regions of Arizona, ground water is being pumped 10 times faster than the natural recharge of the aquifers (Pimentel et al., 2004b).

All these factors suggest that the environmental system in which U.S. corn is being produced is being rapidly degraded. Further, it substantiates the conclusion that the U.S. corn production system is not environmentally sustainable now or for the future, unless major changes are made in the cultivation of this major food/feed crop. Corn is raw material for ethanol production, but cannot be considered to provide a renewable energy source.

Major air and water pollution problems also are associated with the production of ethanol in the chemical plant. The EPA (2002) has issued warnings to ethanol plants to reduce their air pollution emissions or be shut down. Another pollution problem is the large amounts of wastewater that each plant produces. As mentioned, for each liter of ethanol produced using corn, about 13 L of wastewater are produced. This wastewater has a biological oxygen demand (BOD) of 18,000–37,000 mg/L depending of the type of plant (Kuby et al., 1984). The cost of processing this sewage in terms of energy (4 kcal/kg of BOD) was included in the cost of producing ethanol (Table 21.2).

Ethanol contributes to air pollution problems when burned in automobiles (Youngquist, 1997; Hodge, 2002, 2003). In addition, the fossil fuels expended for corn production and later in the ethanol plants amount to expenditures of 6597 kcal of fossil energy per 1000 L of ethanol produced (Table 21.2). The consumption of the fossil fuels release significant quantities of pollutants to the atmosphere. Furthermore, carbon dioxide emissions released from burning these fossil fuels contribute to global warming and are a serious concern (Schneider et al., 2002). When all the air pollutants associated with the entire ethanol system are measured, ethanol production contributes significantly to the serious U.S. air pollution problem (Youngquist, 1997; Pimentel, 2003). Overall, if air pollution problems were controlled and included in the production costs, then ethanol production costs in terms of energy and economics would be significantly increased.

NEGATIVE OR POSITIVE ENERGY RETURN?

Shapouri et al. (2004) of the USDA are now reporting a net energy positive return of 67%, whereas in this chapter, we report a negative 29% deficit. In their last report, Shapouri et al. (2002) reported a net energy positive return of 34%. Why did ethanol production net return for the USDA nearly double in 2 years while corn yields in the United States declined 6% during the past 2 years (USDA, 2002, 2003a)? Shapouri results need to be examined.

1. Shapouri et al. (2004) omit several inputs, for instance, all the energy required to produce and repair farm machinery, as well as the fermentation–distillation equipment. All the corn production in the United States is carried out with an abundance of farm machinery, including tractors, planters, sprayers, harvesters, and other equipment. These are large energy inputs in corn ethanol production, even when allocated on a life cycle basis.
2. Shapouri used corn data from only 9 states, whereas we use corn data from 50 states.
3. Shapouri reported a net energy return of 67% for the co-products, primarily DDG used to feed cattle.
4. Although we did not allocate any energy related to the impacts that the production of ethanol has on the environment, they are significant in U.S. corn production. Please see comments above (page 317).
5. Andrew Ferguson (2004) makes an astute observation about the USDA data. The proportion of the sun's energy that is converted into useful ethanol, using the USDA's very positive data, only amounts to 5 parts per 10,000. If the figure of 50 million ha were to be devoted to growing corn for ethanol, then this acreage would supply only about 11% of U.S. liquid fuel needs.
6. Many other investigators support our type of assessment of ethanol production. (Please see page 312.)

FOOD VERSUS FUEL ISSUE

Using corn, a human food resource, for ethanol production, raises major ethical and moral issues. Today, malnourished (calories, protein, vitamins, iron, and iodine) people in the world number about 3.7 billion (WHO, 2005). This is the largest number of malnourished people and proportion ever reported in history. The expanding world population that now number 6.5 billion complicates the food security problem (PRB, 2004). More than a quarter million people are added each day to the world population, and each of these human beings requires adequate food.

Malnourished people are highly susceptible to various serious diseases; this is reflected in the rapid rise in the number of seriously infected people in the world as reported by the World Health Organization (Kim, 2002).

The current food shortages throughout the world call attention to the importance of continuing U.S. exports of corn and other grains for human food. Cereal grains make up 80% of the food of the people worldwide. During the past 10 years, U.S. corn and other grain exports have nearly tripled, increasing U.S. export trade by about $3 billion per year (USBC, 2003).

Concerning the U.S. balance of payments, the United States is importing more than 61% of its oil at a cost of more than $75 billion per year (USBC, 2003). Oil imports are the largest deficit payments incurred by the United States (USBC, 2003). Ethanol production requires large fossil energy input, therefore it is contributing to oil and natural gas imports and U.S. deficits (USBC, 2003).

At present, world agricultural land based on calories supplies more than 99.7% of all world food (calories), while aquatic ecosystems supply less than 0.3% (FAO, 2001). Already, worldwide, during the last decade per capita available cropland decreased 20%, irrigation 12%, and fertilizers 17% (Brown, 1997). Expanding ethanol production could entail diverting valuable cropland from producing corn needed to feed people to producing corn for ethanol factories. This creates serious practical as well as ethical problems. Thus, the practical aspects, as well as the moral and ethical issues, should be seriously considered before steps are taken to convert more corn into ethanol for automobiles.

SWITCHGRASS PRODUCTION OF ETHANOL

The average energy input per hectare for switchgrass production is only about 2.8 million kcal/year (Table 21.3). With an excellent yield of 10 t/ha/year, this suggests that for each kcal invested as fossil energy the return is 11 kcal—an excellent return. If pelletized for use as a fuel in stoves, the return is reported to be about 1:14.6 kcal (Samson et al., 2004). The 14.6 is higher than the 14.4 kcal in Table 21.3, because here a few more inputs were included than in Samson et al. (2004) report. The cost per ton of switchgrass pellets range from $94 to $130 (Samson et al., 2004). This appears to be an excellent price per ton.

However, converting switchgrass into ethanol results in a negative energy return (Table 21.4). The negative energy return is 45% or slightly higher than the negative energy return for corn ethanol production (Tables 21.2 and 21.4). The cost of producing a liter of ethanol using switchgrass was 54¢ or 9¢ higher than

TABLE 21.3
Average Inputs and Energy Inputs per Hectare per Year for Switchgrass Production

Inputs	Quantity	10^3 kcal	Costs ($)
Labor	5 h[a]	20[b]	65[c]
Machinery	30 kg[d]	555	50[a]
Diesel	100 L[e]	1000	50
Nitrogen	50 kg[e]	800	28[e]
Seeds	1.6 kg[f]	100[a]	3[f]
Herbicides	3 kg[g]	300[h]	30[a]
Total	10,000 kg yield[i]	2755	230[j]
	40 million kcal yield	input/output ratio	1:14.4[k]

[a] Estimated.

[b] Average person works 2000 h/year and uses about 8000 L of oil equivalents. Prorated this works out to be 20,000 kcal.

[c] The agricultural labor is paid $13/h.

[d] The machinery estimate also includes 25% more for repairs.

[e] Calculated based on data from David Parrish (personal communication, Virginia Technology University, 2005).

[f] Data from Samson (1991).

[g] Calculated based on data from Henning (1993).

[h] 100,000 kcal/kg of herbicide.

[i] Samson et al. (2000).

[j] Brummer et al. (2000) estimated a cost of about $400/ha for switchgrass production. Thus, the $268 total cost is about 49% lower than what Brummer et al. estimate and this includes several inputs not included in Brummer et al.

[k] Samson et al. (2000) estimated an input per output return of 1:14.9, but we have added several inputs not included in Samson et al. Still the input/output returns are similar.

TABLE 21.4
Inputs per 1000 L of 99.5% Ethanol Produced from U.S. Switchgrass

Inputs	Quantities	kcal × 1000[a]	Costs ($)
Switchgrass	2,500 kg[b]	694[c]	250[d]
Transport, switchgrass	2,500 kg[e]	300	15
Water	125,000 kg[f]	70[g]	20[h]
Stainless steel	3 kg[i]	45[i]	11[i]
Steel	4 kg[i]	46[i]	11[i]
Cement	8 kg[i]	15[i]	11[i]
Grind switchgrass	2,500 kg	100[j]	8[j]
Sulfuric acid	118 kg[k]	0	83[l]

TABLE 21.4 (continued)
Inputs per 1000 L of 99.5% Ethanol Produced from U.S. Switchgrass

Inputs	Quantities	kcal × 1000[a]	Costs ($)
Steam production	8.1 tons[k]	4404	36
Electricity	660 kWh[k]	1703	46
Ethanol conversion to 99.5%	9 kcal/L[m]	9	40
Sewage effluent	20 kg (BOD)[n]	69[o]	6
Total		7455	537

Requires 45% more fossil energy to produce 1 L of ethanol using 2.5 kg switchgrass than the energy in a liter of ethanol. Total cost per liter of ethanol is 54¢.

A total of 0.25 kg of brewer's yeast (80% water) was produced per 1000 L of ethanol produced. This brewer's yeast has a feed value equivalent in soybean meal of about 480 kcal.

[a] Outputs: 1000 L of ethanol = 5.13 million kcal.

[b] Samson (1991) reports that 2.5 kg of switchgrass is required to produce 1 L of ethanol.

[c] Data from Table 21.3 on switchgrass production.

[d] Samson et al. (2004).

[e] Estimated 144-km roundtrip.

[f] Pimentel et al. (1988).

[g] Estimated water needs for the fermentation program.

[h] Pimentel (2003).

[i] Slesser and Lewis (1979).

[j] Calculated based on grinder information (Wood Tub Grinders, 2004).

[k] Estimated based on cellulose conversion (Arkenol, 2004).

[l] Sulfuric acid sells for $7 per kg. It is estimated that the dilute acid is recycled 10 times.

[m] 95% ethanol converted to 99.5% ethanol for addition to gasoline (T. Patzek, personal communication, University of California, Berkeley, 2004).

[n] 20 kg of BOD per 1000 L of ethanol produced (Kuby et al., 1984).

[o] 4 kWh of energy required to process 1 kg (Blais et al., 1995).

the 45¢/L for corn ethanol production (Tables 21.2 and 21.4). The two major energy inputs for switchgrass conversion into ethanol were steam and electricity production (Table 21.4).

WOOD CELLULOSE CONVERSION INTO ETHANOL

The conversion of 2500 kg of wood harvested from a sustainable forest into 1000 L of ethanol requires an input of about 9.0 million kcal (Table 21.5). Therefore, the wood cellulose system requires slightly more energy to produce the 1000 L of ethanol than using switchgrass (Tables 21.4 and 21.5). About 57% more energy is required to produce a liter of ethanol using wood than the energy harvested as ethanol.

TABLE 21.5
Inputs per 1000 L of 99.5% Ethanol Produced from U.S. Wood Cellulose

Inputs	Quantities	kcal × 1000[a]	Costs ($)
Wood, harvest (fuel)	2,500 kg[b]	400[c]	250[n]
Machinery	5 kg[m]	100[m]	10[o]
Replace nitrogen	50 kg[c]	800	28[o]
Transport, wood	2,500 kg[d]	300	15
Water	125,000 kg[e]	70[f]	20[o]
Stainless steel	3 kg[g]	45[g]	11[g]
Steel	4 kg[g]	46[g]	11[g]
Cement	8 kg[g]	15[g]	11[g]
Grind wood	2,500 kg	100[h]	8[h]
Sulfuric acid	118 kg[b]	0	83[p]
Steam production	8.1 tons[b]	4404	36
Electricity	666 kWh[b,l]	1703	46
Ethanol conversion to 99.5%	9 kcal/L[i]	9	40
Sewage effluent	20 kg (BOD)[j]	69[k]	6
Total		8061	575

Requires 57% more fossil energy to produce 1 L of ethanol using 2 kg wood than the energy in a liter of ethanol. Total cost per liter of ethanol is 58¢.

A total of 0.2 kg of brewer's yeast (80% water) was produced per 1000 L of ethanol produced. This brewer's yeast has a feed value equivalent in soybean meal of 467 kcal.

[a] Outputs: 1000 L of ethanol = 5.13 million kcal.

[b] Arkenol (2004) reported that 2 kg of wood produced 1 L of ethanol. We question this 2 kg to produce 1 L of ethanol when it takes 2.69 kg of corn grain to produce 1 L of ethanol. Others are reporting 13.2 kg of wood per kg per liter of ethanol (DOE, 2004). We used the optimistic figure of 2.5 kg of wood per liter of ethanol produced.

[c] 50 kg of nitrogen removed with the 2500 kg of wood (Kidd and Pimentel, 1992).

[d] Estimated 144-km roundtrip.

[e] Pimentel et al. (1988).

[f] Estimated water needs for the fermentation program.

[g] Slesser and Lewis (1979).

[h] Calculated based on grinder information (Wood Tub Grinders, 2004).

[i] 95% ethanol converted to 99.5% ethanol for addition to gasoline (T. Patzek, personal communication, University of California, Berkeley, 2004).

[j] 20 kg of BOD per 1000 L of ethanol produced (Kuby et al., 1984).

[k] 4 kWh of energy required to process 1 kg (Blais et al., 1995).

[l] Illinois Corn (2004).

[m] Mead and Pimentel (2006).

[n] Samson et al. (2004).

[o] Pimentel (2003).

[p] Sulfuric acid sells for $7 per kg. It is estimated that the dilute acid is recycled 10 times.

The ethanol cost per liter for wood-produced ethanol is slightly higher than the ethanol produced using switchgrass, 58¢ versus 54¢, respectively (Tables 21.4 and 21.5). The two largest fossil energy inputs in the wood cellulose production system were steam and electricity (Table 21.5).

SOYBEAN CONVERSION INTO BIODIESEL

Various vegetable oils have been converted into biodiesel and they work well in diesel engines. An assessment of producing sunflower oil proved to be energy negative and costly in terms of dollars (Pimentel, 2001). Although soybeans contain less oil than sunflower, about 18% soy oil compared with 26% oil for sunflower, soybeans can be produced without or nearly zero nitrogen (Table 21.6). This makes soybeans advantageous for the production of biodiesel. Nitrogen fertilizer is one of the most energy costly inputs in crop production (Pimentel et al., 2002).

The yield of sunflower is also lower than soybeans, 1500 kg/ha for sunflower compared with 2668 kg/ha for soybeans (USDA, 2003). The production of 2668 kg/ha of soy requires an input of about 3.7 million kcal/ha and costs about $537/ha (Table 21.6).

With a yield of oil of 18% then 5556 kg of soybeans are required to produce 1000 kg of oil (Table 21.7). The production of the soy feedstock requires an input of 7.8 million kcal. The second largest input is steam that requires an input of 1.4 million kcal (Table 21.7). The total input for the 1000 kg of soy oil is 11.4 million kcal. With soy oil having an energy value of 9 million kcal, then there is a net loss of 32% in energy. However, credit should be taken for the soy meal that is produced and this has an energy value of 2.2 million kcal. Adding this credit to soybean oil credit, then the net loss in terms of energy is 8% (Table 21.7). The price per kg of soy biodiesel is $1.21; however, taking credit for the soy meal would reduce this price to 92¢/kg of soy oil. (*Note*: Soy oil has a specific gravity of about 0.92, thus soy oil value per liter is 84¢/L. This makes soy oil about 2.8 times as expensive as diesel fuel.) This makes soy oil still quite expensive compared with the price of diesel that costs about 30¢/L to produce (USBC, 2003).

TABLE 21.6
Energy Inputs and Costs in Soybean Production per Hectare in the United States

Inputs	Quantity	kcal × 1000	Costs ($)
Labor	7.1 h[a]	284[b]	92.30[c]
Machinery	20 kg[d]	360[e]	148.00[f]
Diesel	38.8 L[a]	442[g]	20.18
Gasoline	35.7 L[a]	270[h]	13.36
LP gas	3.3 L[a]	25[i]	1.20
Nitrogen	3.7 kg[j]	59[k]	2.29[l]
Phosphorus	37.8 kg[j]	156[m]	23.44[n]
Potassium	14.8 kg[j]	48[o]	4.59[p]
Lime	4800 kg[q]	1349[d]	110.38[q]

(*continued*)

TABLE 21.6 (continued)
Energy Inputs and Costs in Soybean Production per Hectare in the United States

Inputs	Quantity	kcal × 1000	Costs ($)
Seeds	69.3 kg[a]	554[r]	48.58[s]
Herbicides	1.3 kg[j]	130[e]	26.00
Electricity	10 kWh[d]	29[t]	0.70
Transport	154 kg[u]	40[v]	46.20
Total		3746	537.22
Soybean yield 2668 kg/ha[w]		9605	kcal input:output 1:2.56

[a] Ali and McBride (1990).

[b] It is assumed that a person works 2000 h/year and utilizes an average of 8000 L of oil equivalents per year.

[c] It is assumed that labor is paid $13/h.

[d] Pimentel and Pimentel (1996).

[e] Machinery is prorated per hectare and a 10-year life of the machinery. Tractors weigh from 6 to 7 t and harvestors from 8 to 10 t, plus plows, sprayers, and other equipment.

[f] College of Agricultural, Consumer & Environmental Sciences (1997).

[g] Input 11,400 kcal/L.

[h] Input 10,125 kcal/L.

[i] Input 7575 kcal/L.

[j] Economic Research Statistics (1997).

[k] Patzek (2004).

[l] Hinman et al. (1992).

[m] Input 4154 kcal/kg.

[n] Cost 62¢/kg.

[o] Input 3260 kcal/kg.

[p] Cost 31¢/kg.

[q] Pimentel et al. (2002).

[r] Costs about 70¢/kg.

[s] Input 860 kcal per kWh and requires 3 kWh thermal energy to produce 1 kWh electricity.

[t] Goods transported include machinery, fuels, and seeds that were shipped an estimated 1000 km.

[u] Input 0.83 kcal/kg/km transported.

[v] Kassel and Tidman (1999).

[w] USDA (2003).

Sheehan et al. (1998, p. 13) of the Department of Energy also report a negative energy return in the conversion of soybeans into biodiesel. They report “1 MJ of biodiesel requires an input of 1.24 MJ of primary energy.”

Soybeans are a valuable crop in the United States. The target price reported by the USDA (2003) is 21.2¢/kg while the price calculated in Table 21.6 for average inputs per hectare is 20.1¢/kg. These values are close.

TABLE 21.7
Inputs per 1000 kg of Biodiesel Oil from Soybeans

Inputs	Quantity	kcal × 1000	Costs ($)
Soybeans	5556 kg[a]	7800[a]	1117.42[a]
Electricity	270 kWh[b]	697[c]	18.90[d]
Steam	1,350,000 kcal[b]	1350[b]	11.06[e]
Cleanup water	160,000 kcal[b]	160[b]	1.31[e]
Space heat	152,000 kcal[b]	152[b]	1.24[e]
Direct heat	440,000 kcal[b]	440[b]	3.61[e]
Losses	300,000 kcal[b]	300[b]	2.46[e]
Stainless steel	11 kg[f]	158[f]	18.72[g]
Steel	21 kg[f]	246[f]	18.72[g]
Cement	56 kg[f]	106[f]	18.72[g]
Total		11,878	1212.16

The 1000 kg of biodiesel produced has an energy value of 9 million kcal. With an energy input requirement of 11.9 million kcal, there is a net loss of energy of 32%. If a credit of 2.2 million kcal is given for the soy meal produced, then the net loss is 8%.

The cost per kg of biodiesel is $1.21.

[a] Data from Table 21.6.

[d] Data from Singh (1986).

[c] An estimated 3 kWh thermal is needed to produce a kWh of electricity.

[d] Cost per kWh is 7¢.

[e] Calculated cost of producing heat energy using coal.

[f] Calculated inputs using data from Slesser and Lewis (1979).

[g] Calculated costs from Pimentel (2003).

SUNFLOWER CONVERSION INTO BIODIESEL

In a preliminary study of converting sunflower into biodiesel fuel, as mentioned, the result in terms of energy output was negative (Pimentel, 2001). In the current assessment, producing sunflower seeds for biodiesel yields 1500 kg/ha (USDA, 2003) or slightly higher than the 2001 yield. The 1500 kg/ha yield is still significantly lower than soybean and corn production per hectare.

The production of 1500 kg/ha of sunflower seeds requires a fossil energy input of 6.1 million kcal (Table 21.8). Thus, the kcal input per kcal output is negative with a ratio of 1:0.76 (Table 21.8). Sunflower seeds have higher oil content than soybeans, 26% versus 18%. However, the yield of sunflower is nearly one half that of soybean.

Thus, to produce 1000 kg of sunflower oil requires 3920 kg of sunflower seeds with an energy input of 156.0 million kcal (Table 21.9). This is the largest energy input listed in Table 21.9. Therefore, to produce 1000 kg of sunflower oil with an energy content of 9 million kcal, the fossil energy input is 118% higher than the energy content of the sunflower biodiesel and the calculated cost is $1.66 per kg of sunflower oil (Table 21.9). (*Note*: The specific gravity of sunflower oil is 0.92, thus the cost of a liter of sunflower oil is $1.53/L.)

TABLE 21.8
Energy Inputs and Costs in Sunflower Production per Hectare in the United States

Inputs	Quantity	kcal × 1000	Costs ($)
Labor	8.6 h[a]	344[b]	111.80[c]
Machinery	20 kg[d]	360[e]	148.00[f]
Diesel	180 L[a]	1800[g]	93.62[h]
Nitrogen	110 kg[i]	1760[j]	68.08[k]
Phosphorus	71 kg[i]	293[l]	44.03[m]
Potassium	100 kg[i]	324[n]	34.11[o]
Lime	1000 kg[i]	281[d]	23.00[o]
Seeds	70 kg[a]	560[p]	49.07[q]
Herbicides	3 kg[i]	300[r]	60.00[s]
Electricity	10 kWh[d]	29[t]	0.70
Transport	270 kg[u]	68[v]	81.00
Total		6119	601.61
Sunflower	yield 1500 kg/ha[w]	4650	kcal input:output 1:0.76

[a] Knowles and Bukantis (1980).

[b] It is assumed that a person works 2000 h/year and utilizes an average of 8000 L of oil equivalents per year.

[c] It is assumed that labor is paid $13/h.

[d] Pimentel and Pimentel (1996).

[e] Machinery is prorated per hectare and a 10-year life of the machinery. Tractors weigh from 6 to 7 t and harvestors from 8 to 10 t, plus plows, sprayers, and other equipment.

[f] College of Agricultural Consumer & Environmental Sciences (1997).

[g] Input 10,000 kcal/L.

[h] 52¢/L.

[i] Blamey et al. (1997).

[j] Patzek (2004).

[k] Hinman et al. (1992).

[l] Input 4154 kcal/kg.

[m] Cost 62¢/kg.

[n] Input 3260 kcal/kg.

[o] Cost 0.023¢/kg.

[p] Based on 7900 kcal/kg of sunflower seed production.

[q] Costs about 70¢/kg.

[r] Input 860 kcal per kWh and requires 3 kWh thermal energy to produce 1 kWh electricity.

[s] $20/kg.

[t] Input 860 kcal per kWh and requires 3 kWh thermal energy to produce 1 kWh electricity.

[u] Goods transported include machinery, fuels, and seeds that were shipped an estimated 1000 km.

[v] Input 0.83 kcal/kg/km transported.

[w] USDA (2003).

TABLE 21.9
Inputs per 1000 kg of Biodiesel Oil from Sunflower

Inputs	Quantity	kcal × 1000	Costs ($)
Sunflower	3,920 kg[a]	15,990[a]	1.570.20[a]
Electricity	270 kWh[b]	697[c]	18.90[d]
Steam	1,350,000 kcal[b]	1,350[b]	11.06[e]
Cleanup water	160,000 kcal[b]	160[b]	1.31[e]
Space heat	152,000 kcal[b]	152[b]	1.24[e]
Direct heat	440,000 kcal[b]	440[b]	3.61[e]
Losses	300,000 kcal[b]	300[b]	2.46[e]
Stainless steel	11 kg[f]	158[f]	18.72[g]
Steel	21 kg[f]	246[f]	18.72[g]
Cement	56 kg[f]	106[f]	18.72[g]
Total		19,599	1662.48

The 1000 kg of biodiesel produced has an energy value of 9 million kcal. With an energy input requirement of 19.6 million kcal, there is a net loss of energy of 118%. If a credit of 2.2 million kcal is given for the soy meal produced, then the net loss is 96%.

The cost per kg of biodiesel is $1.66.

[a] Data from Table 21.8.

[b] Data from Singh (1986).

[c] An estimated 3 kWh thermal is needed to produce a kWh of electricity.

[d] Cost per kWh is 7¢.

[e] Calculated cost of producing heat energy using coal.

[f] Calculated inputs using data from Slesser and Lewis (1979).

[g] Calculated costs from Pimentel (2003).

CONCLUSION

Several physical and chemical factors limit the production of liquid fuels like ethanol and biodiesel using plant biomass materials. These include the following:

1. An extremely low fraction of the sunlight reaching America is captured by plants. On average, the sunlight captured by plants is only about 0.1%, with corn providing 0.25%. These low values are in contrast to photovoltaics that capture from 10% or more sunlight, or approximately 100-fold more sunlight than plant biomass.
2. In ethanol production, the carbohydrates are converted into ethanol by microbes that on average bring the concentration of ethanol to 8% in the broth with 92% water. Large amounts of fossil energy are required to remove the 8% ethanol from the 92% water.
3. For biodiesel production, there are two problems: the relatively low yields of oil crops ranging from 1500 kg/ha for sunflower to about 2700 kg/ha for soybeans; sunflower averages 25.5% oil, whereas soybeans average 18%

oil. In addition, the oil extraction processes for all oil crops is highly energy intensive as reported in this chapter. Therefore, these crops are poor producers of biomass energy.

REFERENCES

Ali, M.B. and W.D. McBride. 1990. *Soybeans: State Level Production Costs, Characteristics, and Input Use*, 1990. Economic Research Service. Stock no. ERS SB873. 48 pp.

Arkenol. 2004. Our technology: Concentrated acid hydrolysis. www.arkenol.com/Arkenol%20Inc/tech01.html (8/2/04).

Batty, J.C. and J. Keller. 1980. Energy requirements for irrigation. In D. Pimentel (ed.), *Handbook of Energy Utilization in Agriculture*, pp. 35–44. Boca Raton, FL: CRC Press.

Blais, J.F., K. Mamouny, K. Nlombi, et al. 1995. Les mesures deficacite energetique dans le secteur de leau. J.L. Sassville and J.F. Balis (eds.), Les Mesures deficacite Energetique pour Lepuration des eaux Usees Municipales. Scientific Report 405. Vol. 3. INRS-Eau, Quebec.

Blamey, F.P.C., R.K. Zollinger and A.A. Schneiter. 1997. Sunflower production and culture. In A.A. Schneiter (ed.), *Sunflower Technology and Production*, pp. 595–670. Madison, WI: American Society of Agronomy.

Brees, M. 2004. Corn silage budgets for Northern, Central and Southwest Missouri. http://www.agebb.missouri.edu/mgt/budget/fbm-0201.pdf (9/1/04).

Brown, L.R. 1997. *The Agricultural Link: How Environmental Deterioration Could Disrupt Economic Progress*. Washington, D.C.: Worldwatch Institute.

Brummer, E.C., C.L. Burras, M.D. Duffy, et al. 2000. *Switchgrass Production in Iowa: Economic Analysis, Soil Suitability, and Varietal Performance.* Ames, IA: Iowa State University.

CalGasoline. 2002. Ethanol is not a suitable replacement for MTBE. www.calgasoline.com/factetha.htm (9/17/2002).

Citizens for Tax Justice. 1997. More corporate giveaways high on congressional agenda: Citizens for Tax Justice. July 22, 1997. http://www.ctj.org/html/cgive97.htm (9/17/2002).

Coelho, S.T., M.F. Bolognini, O.C. Silva, et al. 2002. Biofuels in Brazil: The current situation. CENBIO—The National Reference Center on Biomass. Technical Texts. http://www.cenbio.org.br/in/index.html (11/12/2002).

College of Agricultural, Consumer and Environmental Sciences. 1997. Machinery cost estimates: Summary of operations. University of Illinois at Urbana-Champaign. www.aces.uiuc.edu/~vo-ag/custom.htm (11/8/01).

Croysdale, D. 2001. Belatedly, DNR concedes our air is clean. *The Daily Reporter.* November 6, 2001. http://www.dailyreporter.com/editorials/eds/nov07/asa11-7.shtml (9/17/2002).

DOE. 2002. Review of transport issues and comparison of infrastructure costs for a renewable fuels standard. U.S. Department of Energy, Washington, D.C. http://tonto.eia.doe.gov/FTPROOT/service/question3.pdf (10/8/2002).

DOE. 2004. Dilute acid hydrolysis. Biomass program. Energy efficiency and renewable energy. U.S. Department of Energy. Washington, D.C. http://www.eere.energy.gov/biomass/dilute_acid.html (11/11/04).

Economic Research Statistics. 1997. Soybeans: Fertilizer use by State. 1996. http://usda.mannlib.cornell.edu/data-sets/inputs/9X171/97171/agch0997.txt (11/11/01).

EPA. 2002. More pollution than they said: Ethanol plants said releasing toxins. *New York Times*, May 3, 2002.

ERAB. 1980 *Gasohol.* Washington, D.C.: Energy Research Advisory Board, U.S. Department of Energy.

ERAB. 1981. *Biomass Energy.* Washington, D.C.: Energy Research Advisory Board, U.S. Department of Energy.

FAO. 2001. *Food Balance Sheets.* Rome: Food and Agriculture Organization of the United Nations.

Ferguson, A.R.B. 2003. Implications of the USDA 2002 update on ethanol from corn. *The Optimum Population Trust.* 11–15.

Ferguson, A.R.B. 2004. Further implications concerning ethanol from corn. Draft manuscript for *the Optimum Population Trust.*

Giampietro, M., S. Ulgiati and D. Pimentel. 1997. Feasibility of large-scale biofuel production. *BioScience* 47(9): 587–600.

Henning, J.C. 1993. *Big Bluestem, Indiangrass and Switchgrass.* Columbia, MO: Department of Agronomy, Campus Extension, University of Missouri.

Hinman, H., G. Pelter, E. Kulp, et al. 1992. Enterprise budgets for fall potatoes, winter wheat, dry beans and seed peas under rill irrigation. Farm Business Management Reports, Columbia, Washington State University, Pullman, WA.

Ho, S.P. 1989. Global warming impact of ethanol versus gasoline. Presented at 1989 National Conference. Clean Air Issues and American Motor Fuel Business. October 1989. Washington, D.C.

Hodge, C. 2002. Ethanol use in US gasoline should be banned, not expanded. *Oil and Gas Journal* September 9, 2002: 20–30.

Hodge, C. 2003. More evidence mounts for banning, not expanding, use of ethanol in gasoline. *Oil and Gas Journal* October 6, 2003: 20–25.

Hoffman, T.R., W.D. Warnock and H.R. Hinman. 1994. Crop enterprise budgets, Timothy-legume and Alfalfa hay, Sudan grass, sweet corn and spring wheat under rill irrigation, Kittitas County, Washington. Farm Business Reports EB 1173, Washington State University, Pullman, WA.

Illinois Corn. 2004. Ethanol's energy balance. http://www.ilcorn.org/Ethanol/Ethan_Studies/Ethan_Energy_Bal/ethan_energy_bal.html (8/10/04).

Kansas Ethanol. 2004. Kansas ethanol: Clean fuel from Kansas farms. http://www.ksgrains.com/ethanol/useth.html (9/11/04).

Kassel, P. and M. Tidman. 1999. *Ag Lime Impact on Yield in Several Tillage Systems, Integrated Crop Management.* Ames, IA: Department of Entomology, Iowa State University.

Kidd, C. and D. Pimentel. 1992. *Integrated Resource Management: Agroforestry for Development.* San Diego, CA: Academic Press.

Kim, Y. 2002. World exotic diseases. In D. Pimentel (ed.), *Biological Invasions: Economic and Environmental Costs of Alien Plant, Animal, and Microbe Species,* pp. 331–354. Boca Raton, FL: CRC Press.

Knowles, P.F. and R. Bukantis. 1980. Energy inputs and outputs for crop systems, field crops: Safflower. In D. Pimentel (ed.), *Handbook of Energy Utilization in Agriculture,* pp. 131–132. Boca Raton, FL: CRC Press.

Kuby, W.R., R. Markoja and S. Nackford. 1984. *Testing and Evaluation of On-Farm Alcohol Production Facilities.* Acures Corporation. Industrial Environmental Research Laboratory. Office of Research and Development. U.S. Environmental Protection Agency: Cincinnati, OH. 100 pp.

Larsen, K., D. Thompson and A. Harn. 2002. Limited and full irrigation comparison for corn and grain sorghum. http://www.colostate.edu/Depts/SoilCrop/extension/Newsletters/2003/Drought/sorghum.html (9/2/2002).

Larson, W.E. and V.B. Cardwell. 1999. History of U.S. corn production. http://citv.unl.edu/cornpro/html/history/history.html (9/2/04).

Lieberman, B. 2002. The ethanol mistake: One bad mandate replaced by another. Competitive Enterprise Institute. http://www.nationalreview.com/comment/comment-lieberman031202.shtml (9/17/2002).

McCain, J. 2003. Statement of Senator McCain on the Energy Bill. Press Release. Wednesday, November 2003.

Mead, D.J. and D. Pimentel. 2006. Use of energy analyses in silvicultural decision-making. *Biomass and Bioenergy* 30: 357–362.

Maiorella, B. 1985. Ethanol. In H.W. Blanch, S. Drew and D.I.C. Wang (eds.), *Comprehensive Biotechnology,* Chapter 43, Vol. 3. New York: Pergamon Press.

NAS. 2003. *Frontiers in Agricultural Research: Food, Health, Environment, and Communities.* Washington, D.C.: National Academy of Sciences. http://dels.nas.edu/rpt_briefs/frontiers_in_ag_final%20for%20print.pdf (11/05/04).

NASS. 1999. National Agricultural Statistics Service. http://usda.mannlib.cornell.edu (30/08/2002).

National Center for Policy Analysis. 2002. Ethanol Subsidies. Idea House. National Center for Policy Analysis. http://www.ncpa.org/pd/ag/ag6.html (9/09/ 2002).

NPRA. 2002. NPRA Opposes Ethanol Mandate; Asks Congress not to Hinder Efforts to Maintain Supply. Washington, D.C.: National Petrochemical & Refiners Association. http://www.npradc.org/news/releases/detail.cfm?docid=164&archive=1 (9/17/2002).

Patzek, T. 2004. Thermodynamics of the corn-ethanol biofuel cycle. *Critical Reviews in Plant Sciences* 23(6): 519–567.

Pimentel, D. 1980. *Handbook of Energy Utilization in Agriculture.* Boca Raton, FL: CRC Press.

Pimentel, D. 1991. Ethanol fuels: Energy security, economics, and the environment. *Journal of Agricultural and Environmental Ethics* 4: 1–13.

Pimentel, D. 1998. Energy and dollar costs of ethanol production with corn. Hubbert Center Newsletter #98/2 M. King Hubbert Center for Petroleum Supply Studies. Golden, CO: Colorado School of Mines. 7pp.

Pimentel, D. 2001. The limitations of biomass energy. In R. Meyers (ed.), *Encyclopedia of Physical Science and Technology.* 3rd ed., Vol. 2, pp. 159–171. San Diego, CA: Academic Press.

Pimentel, D. 2003. Ethanol fuels: Energy balance, economics, and environmental impacts are negative. *Natural Resources Research* 12(2): 127–134.

Pimentel, D. and M. Pimentel. 1996. *Food, Energy and Society.* Boulder, CO: Colorado University Press.

Pimentel, D., A.F. Warneke, W.S. Teel, et al. 1988. Food versus biomass fuel: Socioeconomic and environmental impacts in the United States, Brazil, India, and Kenya. *Advances in Food Research* 32: 185–238.

Pimentel, D., C. Harvey, P. Resosudarmo, et al. 1995. Environmental and economic costs of soil erosion a E. Preiss, et al. 1997. Water resources: agriculture, the environment, and Society. *BioScience* 47(2): 97–106.

Pimentel, D., R. Doughty, C. Carothers, et al. 2002. Energy inputs in crop production: Comparison of developed and developing countries. In R. Lal, D. Hansen, N. Uphoff, et al. (eds.), *Food Security & Environmental Quality in the Developing World*, pp. 129–151. Boca Raton, FL: CRC Press.

Pimentel, D., A. Pleasant, J. Barron, et al. 2004a. U.S. energy conservation and efficiency: Benefits and costs. *Environment Development and Sustainability* 6: 279–305.

Pimentel, D., B. Berger, D. Filberto, et al. 2004b. Water resources: Current and future issues. *BioScience* 54(10): 909–918.

PRB. 2004. World Population Data Sheet. Washington, D.C.: Population Reference Bureau. 2pp.

Samson, R. 1991. Switchgrass: A living solar battery for the prairies. Ecological Agriculture Projects, McGill University (Macdonald Campus, Ste-Anne-de-Bellevue, QC, H9X 3V9 Canada. Copyright @ 1991 REAP Canada).

Samson, R., P. Duxbury, M. Drisdale, et al. 2000. Assessment of Pelletized Biofuels. PERD Program, Natural Resources Canada, Contract 23348-8-3145/001/SQ.

Samson, R., P. Duxbury and L. Mulkins. 2004. Research and development of fibre crops in cool season regions of Canada. Resource Efficient Agricultural Production-Canada. Box 125, Sainte Anne de Bellevue, Quebec, Canada, H9X 3V9. http://www.reap-canada.com/Reports/italy.html (June 26, 2004).

Schneider, S.H., A. Rosencranz and J.O. Niles. 2002. *Climate Change Policy Change.* Washington, D.C.: Island Press.

Shapouri, H., J.A. Duffield and M. Wang. 2002. The energy balance of corn ethanol: An update. USDA, Office of Energy Policy and New Uses, Agricultural Economics. Report No. 813. 14pp.

Shapouri, H., J.A. Duffield, A. McAloon, et al. 2004. The 2001 Net Energy Balance of Corn Ethanol (Preliminary). Washington, D.C.: U.S. Department of Agriculture.

Sheehan, J., V. Camobreco, J. Duffield, et al. 1998. An overview of biodiesel and petroleum diesel life cycles. Nrel/tp-580-24772. National Renewable Energy Laboratory. U.S. Department of Energy.

Singh, R.P. 1986. Energy accounting of food processing. In R.P. Singh (ed.), *Energy in Food Processing,* pp. 19–68. Amsterdam: Elsevier.

Slesser, M. and C. Lewis. 1979. *Biological Energy Resources.* New York: Halsted.

Spirits Low. 1999. Spirits low as Brazil alcohol car in trouble anew. Reuters Limited. November 22, 1999. http://www.climateark.org/articles/1999/alcocaro.htm (11/15/04).

Stanton, T.L. 1999. Feed composition for cattle and sheep. Colorado State University. Cooperative extension. Report No. 1.615. 7 pp.

USBC. 2003. *Statistical Abstract of the United States 2003.* Washington, D.C.: U.S. Bureau of the Census, U.S. Government Printing Office.

USCB. 2004. *Statistical Abstract of the United States 2003.* Washington, D.C.: U.S. Census Bureau, U.S. Government Printing Office.

USDA. 1991. Corn-State. Costs of Production. Washington, D.C.: U.S. Department of Agriculture, Economic Research Service, Economics and Statistics System, Stock #94018.

USDA. 1997a. *Farm and Ranch Irrigation Survey (1998).* 1997 Census of Agriculture. Vol. 3, Special Studies, Part 1. 280 pp.

USDA. 1997b. 1997 Census of agriculture. U.S. Department of Agriculture. http://www.ncfap.org (8/28/2002).

USDA. 2002. *Agricultural Statistics.* Washington, D.C.: U.S. Government Printing Office.

USDA. 2003a. *Agricultural Statistics.* Washington, D.C.: USDA. I–1– XV-34 pp.

USDA. 2003b. Agricultural Chemicals and Production Technology: Questions and Answers. Economic Research Service. U.S. Department of Agriculture. http://www.ers.usda.gov/Briefing/AgChemicals/Questions/nmqa5.htm (update 11/12/2002) (9/1/04).

Wereko-Brobby, C. and E.B. Hagan. 1996. *Biomass Conversion and Technology.* Chichester: John Wiley & Sons.

WHO. 2000. Nutrition for health and development: A global agenda for combating malnutrition. http://www.who.int/nut/documents/nhd_mip_2000.pdf (11/3/04).

WHO. 2005. Malnutrition Worldwide. World Health Organization. http:// www.mikeschoice.com/reports/malnutrition_worldwide.htm (1/3/07).

Wilcke, B. and J. Chaplin. 2000. Fuel saving ideas for farmers. Minnesota/Wisconsin Engineering Notes. http://www.bae.umn.edu/extens/ennotes/enspr00/fuelsaving.htm (9/2/04).

Wood Tub Grinders. 2004. Wood tub grinders. http://p2library.nfesc.navy.mil/P2_Opportunity_Handbook/7_III_13.html (8/3/04).

Youngquist, W. 1997. *GeoDestinies: The Inevitable Control of Earth Resources over Nations and Individuals.* Portland, OR: National Book Company.

Youngquist, W. and R.C. Duncan. 2003. North American natural gas: Data show supply problems. *Natural Resources Research* 12(4): 229–240.

22 U.S. Energy Conservation and Efficiency: Benefits and Costs

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Energy use in the United States increased nearly 40% from 1970 to 2000 (USBC, 2001). Projections are that it will increase by an additional 40% by the year 2020. The finite energy resources of petroleum, natural gas, coal, and other mined fuels provide the United States with about 93% of its energy needs at a cost of $567 billion/year (USBC, 2001). With increasing energy shortages and prices, this growth over the next two decades cannot continue (Abelson, 2000; Duncan, 2001).

The United States now imports more than 60% of its oil at an annual cost of about $75 billion driving the major trade imbalance (USBC, 2001). The United States has already consumed from 82% to 88% of its proved oil reserves (API, 1996; API, 1999). Projections are that the United States will have to import from 80% to 90% of its oil within 20 years, based on production, import, and consumption trends and forecasts (USBC, 2001; BP, 2001; M. Energy Rev.; 2001; W. Youngquist, consulting geologist, Eugene, Oregon, personal communication, 2002).

The entire U.S. economy, standard of living, and indeed national security depend on the availability of large quantities of fossil energy. Each American uses nearly 8000 L/year of oil equivalents for all purposes, including transport, industry, residential, and food (USBC, 2001). Furthermore, with the U.S. population adding 3.3 million people per year and projected to double in 70 years, providing energy resources will be increasingly difficult (USBC, 2001; Pimentel et al., 2002a).

The growing imbalance between declining energy supplies and growing energy use signals that the United States faces a serious and escalating energy crisis (based on data in USBC, 2001). This analysis focuses on current energy expenditures and opportunities to reduce U.S. fossil fuel consumption while maintaining a viable economy, environment, and continuing to protect national security.

TRANSPORTATION

The transportation sector is the largest sector for petroleum consumption in the United States, with an estimated 26.4 quads (1 quad = 10^{15} BTU = 1.05×10^{18} J =

293×10^9 kWh = 0.25×10^{15} kcal) consumed each year (DOE, 2000a). At the current growth rate of 2.3%/year, the total amount of oil consumption for transportation is projected to double in just 30 years (USDOT, 1999).

PASSENGER VEHICLES

The 140 million cars, SUVs, and pickup trucks driven by Americans are the largest consumers of fuel oil, an estimated 510 billion L/year of gasoline (USBC, 2001). Of this, approximately 78 million trucks consume slightly less than half the fuel amount (diesel) used by cars, or 150 billion L/year (USBC, 2001), while buses consume about 4 billion diesel L/year (USBC, 2001).

The average car, SUV, and pickup truck use 3640 L/year, and the average fuel economy is 8 km/L (USBC, 2001). Using proven engine design technologies, fuel economies of approximately 16 km/L could be achieved (Greene and DeCicco, 2000). This halving of fuel consumption, once all vehicles have been changed, would result in energy savings of 8 quads/year and consumer savings of about \$102 billion in direct gasoline costs at \$0.40/L (\$1.50/gal). In addition, the U.S. economy would save approximately \$54 billion in indirect, or external costs, from secondary effects such as reduced carbon emissions and reduced reliance on foreign oil imports (NAS, 2001).

Assessments of the introduction of new technologies into the automobile fleet suggest that 15 years are required for the technology to become fully integrated (USEPA, 2001). Projecting a straight-line annual adoption in fuel efficient technologies over 15 years, the total potential of the fuel savings over the first 10 years is estimated to be about 11.0 quads/year (Table 22.1).

There are approximately 770 billion L of gasoline available from Arctic National Wildlife Refuge (ANWR) based on the fact that nearly 74 L of finished gasoline are produced from 159 L (42-gallon barrel) of oil (DOE, 2001a,b). The approximately 775 billion L of gasoline that could be conserved by increased vehicle fuel economy by 2011 would more than replace the amount of oil that could be extracted by opening the ANWR to drilling.

Growing congestion and gridlock on U.S. highways are increasing fuel consumption by cars, trucks, and buses and reducing the productivity of the U.S. economy. For instance, each year in the Los Angeles metropolitan area 684,000 h of labor are lost to vehicle congestion (USBC, 2000). This costs the region about \$12.5 million for fuel and labor costs (TTI, 2001). On average, highway congestion in 70 metropolitan areas results in an annual delay of 40 h per driver per year (TTI, 2001). Those hours spent in traffic with the engine idling waste 318 L of fuel per driver and cost each driver nearly \$1000/year.

Simply to maintain a steady state of congestion, between 3% and 5% of vehicles with single drivers in operation need to convert to car pools or switch to public transportation annually (TTI, 2001). There is considerable opportunity to reduce energy consumption in the transportation sector.

If increased mileage targets for both cars and light trucks were achieved, this would provide societal benefits in reduced greenhouse emissions, reduced national security costs, reduced oil imports, and improved environmental quality (OTA, 1994).

TABLE 22.1
Estimated Primary Energy (Quads) and Dollars ($ Billions) Used and Saved per Year, after Energy-Efficient Technologies and Conservation Strategies Are Implemented after Approximately 10 Years

Energy System	Energy Used	Energy Saved	$ Saved
Transportation	26.4[a]	11.0[b]	181[c]
Automobiles	20.4	8.0	156
Commercial/Freight	6.0	3.0	50
Residential	18.4[a]	5.9[b]	59[c]
Heating and cooling	9.0	3.3	33
Appliances/Equipment	8.0	2.1	21
Lighting	1.4	0.5	5
Commercial	15.1[a]	3.4[b]	44[c]
Heating and cooling	6.5	2.0	20
Equipment	5.0	1.8	18
Lighting	2.1	0.6	6
Food system	(15.8)[d]	4.8[b]	48[c]
Industry	36.5[a]	5.9[b]	42[c]
General industry-wide	13.3	3.5	35
Paper and wood products	3.1	0.5	5
Chemicals	7.0	1.0	1
Metals	2.8	0.8	1
Plastics	2.0	0.1	0.1
Other	7.3	0.0	0
Energy subsidies withdrawn	—	1.0[b]	39[b]
Total	96.4	32.0	438

[a] USBC (2001).
[b] See text.
[c] Estimated.
[d] Energy inputs included in other sectors.

The various improvements mentioned, if implemented, could save an estimated 5 quads/year in U.S. energy consumption during the next decade.

FREIGHT TRANSPORTATION

Freight transportation is a major sector in the U.S. economy and uses a significant quantity of energy, about 6 of the 26.4 quads consumed by transportation each year (OTA, 1994). Trucks account for about 80% of the 6 quads of energy in the transportation sector and transports about 30% of total U.S. goods, typically characterized as nonbulk cargo, like food supplies (OTA, 1994; USBTS, 2000). Trucks generally are used to transport goods relatively short distances, or about 715 km (USBTS, 2000), and are relatively expensive in terms of energy used, requiring 0.82 kWh/ton/km, and costing about 16¢/ton/km (ORNL, 2000).

Railroads account for another 30% of the goods transported in the United States (OTA, 1994; USBTS, 2000). The average distance of goods transported by rail is 1345 km (USBTS, 2000). In comparison to trucks, railroads primarily accommodate bulk products that are shipped long distance in larger quantities. Rail transport is about four times more energy efficient than trucks, requiring only 0.24 kWh/ton/km and costing only 1.4¢/ton/km (USBTS, 2000; USBC, 2001).

Ships carry about 30% of all U.S. freight shipments of crude oil, refined petroleum products, and combined crude and petroleum products (USBTS, 2000). Ships are relatively energy efficient in the transport of goods, requiring 0.10 kWh/ton/km (Mintz and Vyuas, 1991) and costing only 0.46¢/ton/km (USBTS, 2000). Although more economical in the transport of goods than either trucks or rail, ships are relatively slow.

While petroleum and its products remain one of the primary commodities transported by maritime shipping, pipelines efficiently transport oil and natural gas, accounting for 60%–70% of oil shipments in the United States (USBTS, 2000). Transport by pipeline for these energy supplies costs 1.2¢/ton/km, with an efficiency of 0.21 kWh/ton/km (USBTS, 2000). Compared with trucks, transport of energy supplies by pipeline is four times more efficient.

Air cargo is the most energy-intensive mode of freight transport requiring 26.9 kWh/t/km and costing 53¢/ton/km (USBTS, 2000). Though airfreight transportation accounts for only 1% of total freight transportation energy use (OTA, 1994), it transports goods the longest distance of all freight modes, averaging 1400 km (USBTS, 2000). However, air freight is 112 times less energy efficient than rails.

If all the 490 billion ton-km of long-distance truck traffic shifted to rail, net savings would equal 0.3 quads when only considering propulsion energy (OTA, 1994). In addition, implementation of multimodal transportation may benefit the environment. For example, a $2.4 billion Alameda Corridor project proposes to consolidate 90 miles of track and roadway into one 20-mile direct railway route between Los Angeles and a Long Beach, California port, eliminating approximately 200 at-grade highway crossings and over 15,000 h of vehicle delays accumulated daily. The project also estimates to reduce traffic congestion and noise by 90%, alleviate train stopping by 75%, and truck traffic by 23% due to the ability to move cargo containers faster and more efficiently.

Improving efficiency in freight transport by trucks is targeted as a major potential contributor to savings in energy. Demonstration runs combining commercially available technology, highly trained drivers, and ideal operating conditions yield efficiencies 50%–70% greater than existing transport (OTA, 1994). If all heavy trucks achieved this level of energy efficiency, energy use would decline about 0.9 quads or 15% in total freight transport energy use, assuming that the most efficient heavy trucks available are used (OTA, 1994).

Current data suggest that trucks average about 2 km/L whereas President Clinton's objective was to reach an efficiency of about 9 km/L by 2010 (Wilson, 1999). If truck fuel efficiency quadrupled, about 3.6 quads could be saved along with about $45 billion every year (Wilson, 1999).

In sum, strategic regulation, policy, and improved energy-efficient technology may reduce truck transportation energy use up to 1 quad each year. Additional reductions are possible by energy-efficient innovations developed for alternative modes including air, pipeline, rail, and water. Total savings in commercial/freight energy are estimated to be about 3 quads/year (Table 22.1).

BUILDINGS SECTOR

Buildings account for about 20% total primary energy consumption in the United States (USBC, 2001). Significant energy savings are possible in both the residential and commercial sectors. Using cost-effective technologies, energy use in the residential sector can be significantly reduced, new commercial buildings can reduce their energy demand by 50%, and existing buildings could achieve a 20% reduction per year (Harris and Johnson, 2000).

HEATING AND COOLING

Residential

Approximately 9 quads of primary energy used yearly in the United States is expended for the space heating and cooling of 103 million households (DOE, 1999a; USBC, 2001). This is more than 50% of all energy consumed for all purposes in the residential sector. Although energy conservation and efficiency have improved significantly over the past 50 years (DOE, 1997), there remains significant potential for future energy savings.

Considerable energy used in residences is lost. For example, an estimated 20%–40% of home heating and cooling energy escapes through leaks in the building shell (Heede et al., 1995; Florman, 1991). Conservation practices, such as caulking and weather-striping can reduce wasteful air leaks from 20% to 50%, with minimal investments (Hafemeister and Wall, 1991; DOE/OBT, 1999; Wilson and Morrill, 1999). Air ducts located in uninsulated crawl spaces lose between 10% and 40% of heating and cooling energy (Cummings et al., 1990; Sherman, 2001). Advanced aerosol-based sealing technology can reduce air leaks by 60%–90%, and save up to 1 quad each year nationwide (CBECS, 1995). Air changes in houses are necessary but this can be achieved with minimal loss of heat or cooling using heat exchangers.

The majority of the homes are under-insulated, an estimated 22% of U.S. homes lack wall insulation and 12% lack ceiling insulation (OTA, 1992). If all residential buildings in the United States were insulated to current model energy code standards, an estimated 1.9 quads of primary energy could be saved each year (NAIMA, 1996). The marginal cost of such insulation in a new home averages $1160, a cost that is returned in less than 10 years (ASE, 2001). In addition in home construction, vinyl siding and windows reduce energy consumption, saving the average homeowner $150–$450 each year in heating and cooling costs compared to other types of windows (APC, 2001).

An estimated 25% or 2 quads of residential heating and cooling energy is lost through the windows (Bevington and Rosenfeld, 1990; Carmody et al., 1996). Window designs on the market today are more than four times as efficient than those sold 30 years ago (Carmody et al., 1996). Within 10 years, the accelerated installation of energy-efficient window technologies during new construction and re-modeling projects would reduce yearly energy losses by 25% (0.43 quads) (Frost et al., 1996).

Emerging window designs that combine high-insulating values with electrochromic technologies, that respond to electric current, temperature, or incident sunlight to control the admission of light energy are even more promising sources of potential energy savings (Roos and Karlsson, 1994). This new technology has the potential to transform residential windows from a $11 billion loss to only a $5 billion loss per year for U.S. homeowners as reduced loss of winter heat and summer cooling energy would more than pay for the window costs within a short period (Frost et al., 1996).

At present only about 0.3 quads of energy per year are being saved by technologies that employ passive and active solar heating and cooling of buildings (Pimentel et al., 2002b). Implementing current technologies and added improvements in passive solar technology will make this approach more effective and less expensive (Busch and Meier, 1986)—especially in the new home market.

As a part of new home construction, the use of new transparent materials in windows makes possible the transmission of from 50% to 70% of incident solar energy while at the same time contributing insulating values typical of 25 cm of fiberglass insulation (Chahroudi, 1992; Twiddell et al., 1994; Forest, 1991). Such materials have a wide range of applications beyond windows, including home heating with transparent, insulated collector-storage walls and integrated storage collectors for domestic hot water (Wittwer et al., 1991).

Over one-third of U.S. homes are heated with natural gas furnaces that have an average efficiency of only 65% (OTA, 1992; Kilgore, 1994). Yet furnaces are available today with efficiencies of 80%–90%. It takes as little as 9 years to repay the costs of replacing an old gas-powered furnace with an efficient one (Cohen et al., 1991).

In only 50% of U.S. households is the heat turned down at night during the winter (Heede et al., 1995; Florman, 1991). Simply lowering the night temperature reduces household energy used for heating by about 17% (about 1 quad) per year in U.S. northern climates (Socolow, 1978).

Over 72% of new homes have air conditioners (Latta, 2000). Air conditioners are available that are 70% more efficient than the average unit sold today (Thorne et al., 2000). This change would save about 40% of the primary energy used in air conditioners and would save 0.5 quads annually in about 10 years (Thorne et al., 2000).

Thus there are many techniques available to reduce heating and cooling losses in homes. New construction and remodeling can reduce energy consumption and save money. If energy conservation and efficient technologies were implemented, an estimated 3.3 quads/year would be saved in the next 10 years. The 3.3 quads is about 1.5 times the total amount of oil that is currently produced in Alaska each year (USBC, 2000).

Commercial

Opportunities for the reduction of heating and cooling energy use in the commercial sector exist through increased implementation of energy-efficient building shell and space conditioning technologies (Davis and Swenson, 1998). For example, at least 20% of commercial buildings are under-insulated (ACEEE, 1996). Upgrading all commercial buildings to insulation standards could save 0.3 quad annually (NAIMA 1996). Advanced computerized energy-management systems can increase energy efficiency by an estimated 25%–50% (ACEEE, 1996). The use of light-colored roofs and trees for shading of buildings could save energy (ACEEE, 1996). With about 6.5 quads of primary energy currently used in the commercial sector for heating and cooling, approximately 2 quads of energy could be saved per year by implementing the energy-efficient technologies and practices discussed in this section (Levine et al., 1996).

EQUIPMENT AND APPLIANCES

The federal government has made significant contributions to energy efficiency in equipment through the Energy Star standards program. By 2020, application of current commercial and residential standards is projected to result in savings of 4.2 quads/year, compared to 2000 (ACEEE 2001). The inclusion of additional standards for 13 appliances and other equipment not yet covered could save an added 0.72 quads/year by 2010 (ACEEE 2001). Thus, when both current and additional standards have been fully adopted by 2020, the total savings will amount to 5 quads of primary energy per year.

Residential

About 8 quads of primary energy (compared to electricity) are used annually to run appliances in the 103 million U.S. households (USBC, 2001). Taken together, appliances account for approximately 22% of electricity consumption in the U.S. residential sector (RECS, 1995). More than 99% of all households have a refrigerator, more than 97% operate a water heater, and a significant number have washing machines (77%), clothes dryers (70%), dishwashers (50%), and freezers (33%). Based on the relatively rapid turnover of home appliances, most appliances will be replaced with more energy-efficient models within a decade (RECS, 1995; Haase, 2001).

Currently, even though equipment prices have risen modestly since the implementation of Energy Star standards, for every dollar invested for an energy-efficient appliance, the consumer saves $3.50 in energy over the life of the appliances (Koomey, et al., 1998; IEA, 2000). In other words, the benefits are more than three times the costs on a net present value basis—yielding an estimated $50 billion in energy cost savings between 1990 and 2000 (LBNL, 2000).

Appliance standards rank with automobile fuel economy standards as the two most effective federal energy-saving policies (ACEEE, 2000). According to analyses by the DOE (2000a), these standards have reduced U.S. electricity use by 2.5% (88 billion kWh/year) by 2000. At present, appliance standards are saving about 1.2 quads of primary energy annually (ASE, 2001). As old appliances and equipment wear out and are replaced, savings from existing standards will steadily grow. By 2010, savings will total more than 250 billion kWh/year (6.5% of projected electricity use), or 2.6 quads of primary energy and reduce current peak demand by approximately 66,000 MW or a 7.6% reduction.

Evidence of the positive effect standards have had on energy efficiency is most apparent in the refrigerator market. In the early 1970s, the average U.S. refrigerator used just under 2000 kWh/year, while the average consumption of the newly designed refrigerators in 1998 used around 500 kWh/year (George et al., 1994; DOE, 2001c). Thus, upgrading refrigerators has the potential to save 1.4 quads/year of primary energy and over $120/year for consumers who replace a vintage model with a product that meets current standards (DOE, 2002a).

Clothes dryers consume the second-largest amount of electricity of the major appliances, costing about $85/year per owner and using more than 1200 kWh/year (DOE, 2002c) or a total of 0.2 quads/year of primary energy. Installing gas dryers that use about half as much primary energy as electric dryers (Cureton and Reed, 1995)—plus placing dryers in warm, dry areas of the home substantially reduces this amount. In addition, inserting sensors for "dryness" can save up to 15% of the energy used in drying clothes (Wilson and Morrill, 1999).

For washing machines, from 85% to 90% of the energy (and for dishwashers about 80%) is used to heat the water (Wilson and Morrill, 1999; DOE, 2002b). Thus, energy use in both washers can be reduced if the hot-water temperature is lowered from the customary 140°F to about 120°F (Wilson and Morrill, 1999; DOE, 2002c). Reducing the water temperature prevents the loss of heat while water is transferred through piping from the water heater to the dishwasher and washing machine. In addition, since newer models have a greater capacity to clean effectively, water hotter than 120°F is no longer necessary to efficiently wash dishes or clothes. Further savings are possible through the use of horizontal-axis washing machines because they use one-third less water than vertical axis machines (Sustainable Sources, 2002).

In addition to the major appliances, a broad array of numerous types of appliances (e.g., computers and other electronic equipment) are projected to account for over 90% of future residential energy growth in about a decade (Sanchez et al., 1998). Approximately 20% of residential electrical appliances are "leaking electricity" or energy is being consumed when the appliances are not performing. If standby power of all appliances with a standby mode were reduced to 1 W, the potential savings would be 21 Twh/year (0.2 quads of primary energy) and roughly $1– $2 billion annually (Sanchez et al., 1998).

Based on the use of new designs and new technologies for appliances it is possible to provide significant energy savings within 10 years (Mortier, 1997; Nadel, 1997; Haase, 2001). Allowing a decade for substantial turnover of the most inefficient appliances, DOE (2002d) estimates are that a 30% decrease in energy consumption (about 2.1 quads of primary energy) can be achieved, at savings of approximately $42 billion/year.

Commercial

Commercial equipment consumes an estimated 7 quads of primary energy per year. The main energy users are water heaters, refrigerators, and cooking stoves. Although previous energy conservation and efficiency efforts have focused on heating and cooling and lighting, commercial equipment represents an important opportunity for energy savings. Allowing a decade for substantial replacement of inefficient equipment with energy-efficient types, an estimated 1.5 quads/year of primary energy could be saved. Going beyond Energy Star implementation, other technologies could save an additional 0.1 quad/year by 2010 (LBNL, 1995). Estimates are that energy-saving software and power management practices have the potential to save about 0.2 quad/year (Levine et al., 1996).

LIGHTING

Lighting offers several opportunities to conserve energy (Turiel et al., 2001). Lighting consumes 14% of all electricity used in the United States (DOE, 2002f). For commercial buildings, lighting accounts for 40% of electricity use and requires another 10% of the electricity to cool the unwanted heat (Romm, 2002). In residential and commercial establishments, about 50% of lighting energy is wasted by obsolete equipment, poor maintenance, or inefficient use (DOE, 1995).

Residential

U.S. residential lighting consumes about 1.4 quads of primary energy per year and represents about 10%–15% of total U.S. residential electricity use (DOE, 2000b). Per household this translates to an average of 1023 kWh/year in lighting costs (DOE, 2002f; USBC, 2001). A small number of lighting fixtures in homes account for a disproportionate percentage of electricity use (Jennings et al., 1997). Thus, incandescent bulbs that are the least expensive to purchase but the most expensive to operate remain the most popular type of lighting (DOE, 1995; DOE, 1996). About 27% of incandescent fixtures account for over 80% of residential lighting electrical use (Jennings et al., 1997).

Compact fluorescent lights (CFL) use 25% as much electricity as incandescent lamps and last up to 10 times longer (EELA 1999). Although many households have installed some type of fluorescent light in an effort to conserve energy, the full efficiency benefits are not realized because the lights are often installed without consideration of usage times (Jennings et al., 1997). For maximum energy savings, lights that are on for four or more hours per day should be targeted for replacement with high-efficiency bulbs (Jennings et al., 1997). A look at the types of lighting by usage time reveals that 42% of households use some type of fluorescent light, but only 13% of lights used for one or more hours per day are fluorescent (DOE, 1996). There is also a connection between residential light fixture location and length of usage times (DOE 1996). The largest consumers of light energy by location and usage times were found to be ceiling and wall fixtures in kitchens, living rooms, and bathrooms, which suggests that replacing these lights with CFL lights will yield substantial savings (Jennings et al., 1997). If all residential incandescent bulbs used for 4 h or more per day were replaced with CFLs, about 1 quad of primary energy, or $8.4 billion, would be saved annually.

Halogen floor lamp torchieres have become popular in recent years, but unfortunately are extremely inefficient, converting only 10% of energy into visible light, as well as being a fire hazard. If the 50 million halogen torchieres in the United States were replaced with CFL torchieres, the energy savings over 5 years would be 53%, or 0.11 quads of primary energy (Kubo et al., 2001). If all these changes were implemented for residences, there would be an estimated savings of 0.47 quad of primary energy per year.

Commercial

In the commercial sector, lighting is an important energy application and accounts for 3.6 quads of primary energy use (DOE, 2002f). In contrast to homes, 77% of commercial floor space is lit by fluorescent lighting and only 14% by incandescent lights (CBECS, 1995). Thus, for commercial buildings, a good method of increasing energy savings would be to upgrade existing lights with more efficient hardware and better lighting maintenance. Historically, commercial lighting systems have been designed to provide about 20% more illumination than actually required (NLB, 2001). Better lighting system maintenance and replacing fluorescent bulbs and other lights on a routine basis could save

0.3 quads of primary energy per year (NLB, 2001). Replacing magnetic ballasts in fluorescent lights with improved electromagnetic ballasts would save from 25% to 40%, or about 0.3 quads of primary energy per year (RMI, 1994). About 48% of commercial floor space is lit using some type of energy-efficient ballast (CBECS, 1995). With implementation of these measures, a conservative estimated savings for the commercial sector would be 0.6 quads of primary energy per year, or about $6 billion annually (Table 22.1).

INDUSTRIAL SECTOR

The industrial sector consumes 24.5 quads of primary energy per year (DOE, 2000a). Three major sectors—paper and wood, chemicals (including plastics and rubber), and primary metals—account for over 85% of the total energy use in the industrial sector (DOE, 2000a). Energy use in the industrial sector is predicted to increase at an annual rate of 0.9%, with primary energy use being close to 30 quads by 2015 (DOE, 1999a).

Significant energy savings can be achieved across the entire sector by implementing broad-based improvements. Optimization of motor systems, compressed air and pumps, use of advanced combined heating and power systems, and improvements in lighting design and technology are some examples of improvements that could save the industrial sector 3.5 quads of energy by 2015 (Martin et al., 2000a). Implementing these changes is, in many cases, limited by a lack of knowledge (Martin et al., 2000a). However, most of these modifications and changes have payback periods of 1–5 years (Martin et al., 2000a).

PAPER, LUMBER, AND OTHER WOOD PRODUCTS

The paper industry uses approximately 2.6 quads and the lumber and wood products industry consumes about 0.5 quads/year. The industry decreased primary energy use by 27% from 1970 to 1994 using new improved technologies, but there is potential to further decrease energy consumption (Martin et al., 2000b).

The production of paper is a multistep process requiring a large number of chemicals plus heat and electrical energy. Each paper product requires different energy inputs based on various pulping and drying needs. For example, estimates are that the production of corrugated paper requires 15 kWh/kg, while the production of bleached Kraft paper requires about 21 kWh/kg (Table 22.2).

Currently, approximately 42% of all U.S. paper products are recycled (USBC, 2001). The amount of recycled pulp that may be used for a given type of paper is limited due to the reduced strength in recycled pulp. Many items, like corrugated cardboard, may be produced from 100% recycled paper, but printing paper may only contain a maximum of 16% recycled pulp (Gunn and Hannon, 1983). Using recycled pulp results in a 27% energy saving per kilogram of recycled corrugated paper and 36% energy saving in printing paper (Selke, 1994; Gunn and Hannon, 1983). However, some high quality paper products are more efficiently produced from virgin fibers than recycled paper in terms of energy (Gunn and Hannon, 1983).

The paper industry has been successful in decreasing energy inputs by burning its biomass wastes, including bark, some wood chips, hogged fuel (unusable chunks of wood), and black liquor (a thick sludge containing lignin). Proven technologies

TABLE 22.2
Energy Inputs (kWh/kg) for Virgin and Recycled Materials

Materials	Virgin	Recycled	Source
Aluminum	15	1.5	International Aluminum Institute (2001); Facts at a Glance (1999)
Corrugated paper	15	11	Selke (1994)
Kraft paper	21	14	Gunn and Hannon (1983)
Steel	17	6	Doering (1980); Facts at a Glance (1999)
Glass	5.5	4.2	Selke (1994)
Plastic	12	5	DOE (2001h)

successfully dewater black liquor to a 65%–75% solids content so it can be burned in mills utilizing the Kraft chemical recovery process, the method by which 80% of pulp is manufactured in the United States (Martin et al., 2000b). The energy cost of dewatering and combustion can increase electricity demand from 0.5% to 1%, but can supply enough heat energy for a small amount of primary energy (Simonsen et al., 1995). The efficiency of biomass combustion can be further increased by cogenerating electrical energy, making it possible for the mill to meet all of its energy demands through biomass fuel (Pimentel, 2001).

Because of the capital intensive nature of the paper industry, turnover of equipment is typically between 35 and 40 years, making it difficult for many new energy-saving technologies to rapidly achieve market penetration (Sheahen and Ryan, 1983). Energy-efficient technologies that are close to becoming feasible, such as black liquor gasification and improvements in heat recovery, are 20%–40% more efficient than current methods, but will only see limited (~20%) application by 2015 (Martin et al., 2000a). Adapting paper mill boilers to burn wood waste is one short-term possibility to reduce energy use with a minimum of additional expense (Martin et al., 2000b).

In the lumber and wood-product industry, the primary use of energy is for drying wood materials (NTIS, 2001). In the past, all wood was air dried, but as drying time has been reduced, energy demands have increased through the use of heated kilns. The combination of lowest operating cost and lowest energy cost has been found by combining air and kiln drying (DOE, 1999b). In many modern mills, sufficient wood waste is produced to provide all the heat needs and, in some cases, exceed energy demands (DOE, 1999b). As new technologies are implemented, the lumber industry may become a supplier of heat and electrical energy (DOE, 1999b).

Martin et al. (2000b) investigated energy efficiency in the paper and pulp industry. They examined 45 different technologies that could reduce energy use within the industry and calculated penetration rates, retrofit and implementation costs. At current energy prices, they estimate that 16%–22% of the primary energy used in the paper and pulp industry could be saved by about 0.5 quad/year (Martin et al., 2000b). The 22% represents an increased use of recycled paper in new paper production. A further 5% saving of primary energy use could be achieved by 2015, using new emerging energy-efficient technologies (Martin et al., 2000a).

CHEMICAL INDUSTRY

The chemical industry uses about 7 quads/year (DOE, 2000d,e) to produce more than 70,000 different chemicals. Although there are seven major chemical sectors within the chemical industry, the major energy consumers are the production of organic chemicals and inorganic chemicals (DOE, 2000c). Just over half of the fuel consumed in the chemical industry is used as a feedstock (e.g., petroleum) consisting of liquefied gases, heavy liquids, and natural gas (Worrell et al., 2000). The main sources of processing energy are natural gas (64%) and electricity (18%) (Worrell et al., 2000).

Although improvements in energy efficiency in the chemical industry have been relatively stagnant for the past 15 years, the industry has demonstrated some significant efficiencies (CMA, 1998). Due to high energy prices in the early 1970s, the industry improved efficiency by 35% from 1974 to 1986 (CMA, 1998). Much of this gain came about with overall improved energy management and increased use of co-generated heat. Current energy improvements may be more difficult or more reaction specific, as many of the broad-based efficiency programs have already been instituted.

The production of organic chemicals requires a large expenditure of energy (2.1 quads or 34% of the energy used in the chemical industry) part of which is petroleum-derived products. The major organic chemicals produced are ethylene and propylene, used as precursors for plastics and alcohols, solvents, and acids, used in other chemical and industrial processes (DOE, 2000e). The production of ethylene and its coproducts consumes nearly 30% of the total energy used by the chemical industry (Worrell et al., 2000). Nearly 72% of this energy goes into the feedstock or petroleum required for ethylene production (PNNL, 1994), but improvements in efficiency are possible (Worrell et al., 2000).

About 18 million tons of nitrogen fertilizer are used in U.S. agriculture each year (CMA, 1998). With nitrogen fertilizer being one of the most energy-intensive products, improving the efficiency of production should be a priority. There are several viable energy-efficient options regarding ammonia synthesis (ammonia being the primary nitrogen source for fertilizer). Currently, ammonia is catalytically made by the Haber-Bosch process. Catalyst improvements could significantly increase efficiency (PNNL, 1995). Implementing the autothermal reforming of ammonia, which combines the partial oxidation of methane and steam reforming, could reduce fuel used in ammonia production by 24%, and reduce the primary feedstock input by 20% (Martin et al., 2000b).

Within the inorganic chemical segment, the production of chlorine and sodium hydroxide is the largest energy consumer. These chemicals are produced through the electrolysis of brine solutions. The most commonly used electrolytic cells, the diaphragm-type, are approximately 6% less efficient than the state-of-art ion-selective membrane cells (DOE, 2000e). Therefore, with the widespread use of the ion-solution membrane, considerable energy can be saved.

Overall, the chemical industry has great potential for improvements in catalytic efficiencies because catalysts are used in about 80% of the chemical industry and consume significant amounts of energy (Martin et al., 2000b). Future catalysts could lower energy consumption 10% or more during the next 10 years (PNNL, 1995; Martin et al., 2000b).

The expanded use of heat recovery systems could save 4% of total energy use in the chemical industry (Martin et al., 2000b). The industry currently uses cogeneration, but more efficient technologies would allow for heat exchangers to be placed in environments previously too harsh to support them. These environments include the production of sodium hydroxide/chlorine and nitric acid (Reay, 1999). In addition, new heat exchangers use novel alloys and designs to prevent corrosion. Payback time on these devices is approximately 2.4 years, thus making the changes economic (Martin et al., 2000b).

In the United States, approximately 9% of the consumed plastics are recovered (Martin et al., 2000b). This figure is low because collection and reuse of postconsumer plastics is often more expensive than the use of virgin material (Martin et al., 2000b). Much of the unrecycled plastic comes from discarded automobiles. Current research is focused on technology processes that allow for plastics of similar density to be separated. Due to the high energy demand of processing plastics like polyethylene, the energy savings from the recycling could be as high as 70% in primary energy savings (Martin et al., 2000b).

The potential energy savings possible for the U.S. chemical industry in the next decade is estimated to be about 1 quad/year.

METALS

In 1997, the production of steel, aluminum, and other metal products accounted for approximately 2.5–2.8 quads of primary energy expended in the entire industrial sector (USBC, 2001). Most of the energy used is in the recovery and manufacturing processes. New methods and technologies have encouraged the metal industry to invest in secondary metals. Secondary or recycled metals consume less energy to produce (Ayres, 1997).

Steel production uses 1.8 quads of the total energy used in the metals industry (DOE, 2000f, 2001g) or 7.5% of the energy used in the industrial sector. The steel industry accounts for 2% of total US energy consumption (DOE, 2001g). For all metals, approximately 60% of that energy is derived from coal for all metals, while electricity and natural gas supply the remaining energy used (AISI, 2001). The production of 1 t of steel requires 5560 kWh (AISI, 2001). From 15% to 20% or approximately $55 per ton is spent on the energy costs (AISI, 2001). The aluminum industry consumes 1.8% of energy in the industrial sector (DOE, 2001d,e,f). In 1995, the primary production of aluminum used nearly 0.5 quads/year of primary energy (DOE, 1997). Nearly 85% of the energy used by the aluminum industry is electricity (DOE, 2000b). Approximately one-third of manufacturing costs are spent on the energy necessary for production.

Through a variety of methods and currently available technologies, the iron and steel industry should be able to decrease energy use by 0.32 quads, or 16% (Worrell et al., 1999). By 2010, the steel industry hopes to reduce energy expenditure from 4760 to 3970 kWh/t (DOE, 2000f). The methods involved in saving energy include simple measures, such as preventive maintenance, better control and recovery of heat through improvements in insulation, controls and sensors, plus cogeneration (Worrell et al., 1999; AISI, 2001). Producing 1 kg of recycled steel saves about 65% of the energy needed to produce 1 kg of virgin steel (Table 22.2). In 2000, the use of 70 million tons of steel scrap conserved 0.8 quads of energy or almost 40% of the total energy used in steel production (Danjczek, 2000). That same year, 58% (1.5 million tons) of steel cans, 84% (2.0 million tons) of appliances, and 95% (14.0 million tons) of automobiles were made from recycled steel (SRI, 2001). For the automobile industry, the steel industry has developed stronger and more corrosion resistant products, which will help automobile manufacturers to improve fuel efficiency (AISI, 2001).

Over the past decade, the amount of energy required to produce primary aluminum has dropped from 26.4 to 15.4 kWh/kg, with the most efficient smelters able to produce at 13 kWh/kg (Aluminum Association, 2001a; DOE, 1997). Most of the future energy savings will come from recycling scrap metal. In 2001, 33% of the 10.69 million metric tons of aluminum was reclaimed each year (Aluminum Association, 2001b). Recycled aluminum uses only 10% of the energy needed to produce aluminum from virgin materials (Table 22.2). Reclamation of aluminum cans has risen to 62% and recycled aluminum comprises about 33% of the sector (DOE, 1997). Aluminum recovery is cost-effective and economically profitable; the industry pays around $990 million to recyclers each year (Aluminum Association, 2001a). If the other 38% of aluminum cans was recycled instead of the additional production of primary aluminum, the amount of primary energy used in the aluminum sector could be reduced by another 12%.

The recovery, reuse, re-manufacturing and recycling of metals is the most promising technology to increase energy (Ayres, 1997). The re-manufacturing, reuse, and repair of products use half of the energy input, but need double the labor input (Ayres, 1997). Although to date resource scarcity has not been a major issue for the metal industries, the cost to extract and mine ores and mineral deposits will increase and become more energy intensive in the future (Ayres, 1997; Youngquist, 1997). Through a combination of recycling, improved methods and technology, we estimate that the metals industry could save about 0.8 quads/year during the next decade.

PLASTICS AND RUBBER

About 4% of total U.S. energy consumption is used to produce raw plastic materials (APC, 2001; APME, 2001). Polyethylene terephthalate (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC), low-density polyethylene (LDPE), polypropylene (PP), and polystyrene (PS) are the six primary resins for plastic manufacturing. The highest consumers of plastic products are automobiles, appliances, food packaging, and the building and construction industries (EPA, 1995). The lightweight durability and versatility of plastics have increased energy efficiencies for many products. As a result, industries have reduced the costs for production, handling, shipping, and transportation (APC, 2001). For food packaging and other packaging, less energy is needed for plastics as compared to other materials. For example, 30% less energy is used to produce foam polystyrene containers, than paperboard containers (APC, 2001).

Substantial energy savings can be gained through the recovery and reuse of plastics. In 2000, the United States recycled 687 million kg of post-consumer plastic bottles such as milk, shampoo, detergent, and soft drinks. However, the average recycling rate is only 27% (APC, 2001).

The major obstacle for more energy gains is the difficulty of available cost-effective recycling technologies (DOE, 2001g). Plastics in housing construction uses the largest volume of material, but little is recycled compared to metals used in construction (DOE, 2001h). Similarly, only 2% of plastics in computers are recovered because of cost-ineffectiveness (DOE, 2001h). Mixed-plastics also pose a significant recycling problem because of hand separation, which is both costly and time-consuming. With assistance from the U.S. Department of Energy and the American Plastics Council, a new system has been developed for the recovery of plastics from mixed plastic streams (DOE, 2001g). If a quarter of the plastics manufacturing sector implements this technology, 0.11 quads can be conserved per year (DOE, 2001g). As its use expands, future capital and installation costs will decrease, and the savings to the entire plastics manufacturing industry could reach $750 million/year (DOE, 2001g).

The energy input for natural rubber production is about 4.2 kWh/kg; this also includes energy input for transport (IRRDB, 2001). Oil is the main component used to manufacture synthetic rubber (Collins, 2000; Jones, 2001). For synthetic rubbers such as butyl rubber, 3.2 kWh/kg is consumed (IRRDB, 2001). Currently the United States consumes 67% of the world's natural rubber production (EP Rubber, 2000). The majority (68%) of natural rubber production is used for tire production while latex products uses 8%, engineering products 7.8%, footwear 5%, and adhesives 3.2% (Jones, 2001).

In 2000, 273 million tons of scrap tires were collected (RMA, 2001). Out of the 273 million, 196 million tons were recycled, while 25 million tons were used to produce tire-derived fuel, and the remaining quantities were used for civil engineering applications such as landfill covers and liners (RMA, 2001).

Retreading tires is cost-effective and environmentally advantageous. Retreading of average truck tires requires 30% less energy than new tires, and saves at least 0.04 quads/year (0.04 quad) (ITRA, 2001). On an average, it takes 83 L of oil (24 kWh/kg) to produce one new truck tire, while retreading one truck tire requires only 26 L (7.6 kWh/kg) (ITRA, 2001).

FOOD SYSTEMS

Each person in the United States consumes about 920 kg (2023 lbs) of food annually, or about 3800 kcal per person per day (USDA, 2001). Supplying this food requires the expenditure of about 15.8 quads of energy per year (USBC, 2001). Put another way, about 13 kcal of fossil energy is expended per kilocalorie of food supplied to each American.

Approximately 7.2 quads/year are expended in the production of crops and livestock (Pimentel et al., 2002a). About two-thirds of the energy used in crop production is for fertilizers plus mechanization (Pimentel et al., 2002a). Excessive use of nitrogen fertilizer is economically and energetically costly to farmers and pollutes the environment (e.g., eutrophication, nitrate contamination of drinking water, and greenhouse gas emissions) (Socolow, 1999). Through proper timing and dosages, the estimate is that nitrogen fertilizer use could be reduced by 25% without reducing crop yields, especially in grain crops (Matson et al., 1998). In addition, if the current soil erosion rate of 13 t/ha/year were reduced to the sustainable level of 1 t/ha/year, this would conserve nearly 17 million tons of fertilizer nutrients and save about 1.5 quads in energy (Troeh et al., 1991; Pimentel et al., 1995). The application of these and other sustainable farming practices hold promise for substantial energy savings (Pimentel et al., 2002a).

Energy conservation is possible while maintaining high crop yields. Currently about 8140 kWh is required to produce 1 ha of conventional corn (Pimentel, 2001). Producing corn using ecologically sound technologies that conserve fertilizers, soil, water, and pesticides, plus reduce the inputs of agricultural mechanization, reduced fossil energy use as much as 50% and the economic costs of production by 33% (Pimentel, 1993). A conservative estimate is that 2.3 quads of energy per year can be saved.

An estimated 7.2 quads of energy are used in food processing and packaging (Pimentel and Pimentel, 1996). At least 10% of the energy in food processing could be conserved through improved efficiency with existing equipment (Casper, 1977). Implementing cogeneration throughout the food processing industry would save up to 40% of current energy inputs (Walshe, 1994). Currently, only 6% of the electricity used in the food industry is produced through cogeneration (Okos et al., 1998). Other promising technologies for energy savings include the use of cold pasteurization and electron beam sterilization, evaporation and concentration by extraction, more efficient drying technologies, and more refrigeration by controlled atmosphere packaging (Okos et al., 1998). Assuming that appropriate technologies were implemented, more than 1 quad of energy might be saved per year (Dalzell, 1994). In total an estimated 4.8 quads/year of energy could be saved in the entire food system each year.

ENERGY SUBSIDIES

Our assessment of subsidies focuses on direct subsidies and does not include subsides allocated to energy-consuming industries and defense energy costs. Federal energy subsidies in the United States total about $39.3 billion each year (Table 22.3). This amounts to $420 per family in taxpayer money per year. Subsidies to the energy industry have the overall effect of making the price of fuels cheaper at the point of purchase. However, the taxpayer pays for this reduction and the negative aspect is that it encourages the consumer to burn more fuel.

The oil industry alone receives as much as $11.9 billion/year in subsidies (Hamilton, 2001) (Table 22.3). This subsidy results in a 3¢ (11¢/gal) price reduction for each liter of gasoline ($1.50/gal). If the consumer were forced to pay the unsubsidized price of gasoline, this would reduce the number of miles driven per consumer. For every 1% increase in the price of gasoline, the number of vehicle-miles traveled is estimated to decline from 0.25% to 0.38% (Merriss, 2001). If the customer paid the unsubsidized price of gasoline, then gasoline consumption would be reduced about 65 billion L/year. This saving would amount to 0.3 just by removing the taxpayer subsidies that the U.S. government pays to oil companies. The most important point is that the public would be paying the real price of gasoline. If less oil were consumed, this could reduce our dependency on imported oil.

TABLE 22.3
Shares of Total Subsidies for Energy Systems

Energy Source	× billion($)	Source
Oil	11.9	Hamilton (2001)
Nuclear	11.0	Koplow (1993)
Coal	8.0	Koplow (1993)
Natural gas	4.3	Koplow (1993)
Energy efficiency	1.2	Koplow (1993)
Ethanol	>1.0	Bioenergy (1996) Reuters (2001)
Renewable energy	0.9	Koplow (1993)
Hydroelectric	0.6	Koplow (1993)
Other	0.4	Koplow (1993)
Total	39.3	

Natural gas has a similar average price elasticity as gasoline. For every 1% increase in price there is approximately a 0.25% decline in consumption (Mackinac, 2001). Electricity has a similar elasticity in the residential sector; thus, for every 1% increase in price there is approximately a 0.23% decline in consumption of electricity (DOE, 2002e).

If the $39 billion in tax subsidies for energy were removed during the next decade, an estimated 1 quad of energy would be conserved.

OIL SUPPLY

The foregoing analyses highlight the dependency of the United States on fossil fuels, not only for personal needs and transportation but also for supporting U.S. industries. In total, Americans use 36.3 quads (1.12×10^{12} L) of oil per year (USBC, 2001). The United States with only 4% of the world population uses 26% of all oil used in the world (BP, 2001). At present, 61% of U.S. oil is imported and this negatively impacts the U.S. balance of payments.

Estimates are that the United States has the potential to ultimately produce only 32.6 to 35.0×10^{12} L of oil before the resources are depleted (MacKenzie, 1996; Deffeyes, 2001). These data suggest that from 82% to 88% of U.S. crude oil reserves have already been utilized, with U.S. oil production peaking in 1970 (API, 1999).

Drilling for oil is energetically and economically costly. Currently, U.S. oil wells are drilled to an average depth of 1708 m (over 1 mile) and cost about $604,000 for each well (API, 1999). Recently, increased drilling effort in the United States has not resulted in increased reserves. U.S. oil discoveries peaked in 1930 (Nehring, 1981). Oil production efficiencies in the United States are illustrated by the fact that the United States has more than 563,000 wells operating, while Saudi Arabia has only about 1600 wells operating (Deffeyes, 2001). Even with 360 times more wells, the United States produces only 80% of the amount that Saudi Arabia does (BP, 2001).

Global oil reserves are estimated to peak in production sometime between 2007 and 2015 with most of the world oil supply lasting approximately 50 years (Duncan and Youngquist, 1999; BP, 2001; Duncan, 2001; Laherrere, 2001; Stone, 2002). The small amount of oil remaining after 2050 will probably be used only for producing plastics and other petrochemicals. Obviously rapid human population growth and increased oil use will determine how long oil resources will last.

CONCLUSION

Through energy conservation and implementation of new energy-efficient technologies, about 32 quads or nearly 33% of U.S. energy consumption and about $438 billion can be saved per year in approximately 10 years (Table 22.1). The sectors having the potential to provide major energy savings are transportation, heating and cooling of residences, industries, and the food system. Other energy-use systems where energy conservation and energy-efficient technologies are possible include chemicals, paper and lumber, household appliances, lighting, and metals. Reducing the $39 billion in taxpayer money spent on subsidies of the energy industries would stimulate the use of conservation and energy-efficient technologies (Tables 22.1 and 22.3).

We are confident that the President and the U.S. Congress working with the people could reduce our energy consumption in approximately a decade by 32 quads/year, about 33% of present energy use. Yet we would be remiss not to point out that continued U.S. population growth (70% of the growth is due to immigration) will generally overwhelm much of proposed energy savings. However, saving fossil energy is fully justified because it would help reduce American dependence on foreign sources of energy and improve national security, improve the environment, reduce the threat of global climate change, and save approximately $438 billion/year which would help support the U.S. economy.

REFERENCES

Abelson, P. 2000. Decreasing reliability of energy. *Science* 290: 931.

ACEEE. 1996. Profiting from energy efficiency. American Council for an Energy Efficient-Economy. http://aceee.org/conf/ssblca.htm (4/16/2002).

ACEEE. 2000. Appliance and equipment efficiency standards: One of America's most effective energy-saving policies. American Council for an Energy Efficient-Economy. http://www.aceee.org/energy/applstnd.htm (3/3/2002).

ACEEE. 2001. Energy star standards. American Council for an Energy Efficient-Economy, Report # A016. http://www.aceee.org/energy/a016full.pdf (3/3/2002).

AISI. 2001. Significant strides in energy efficiency. American Iron and Steel Institute. http://www.steel.org/facts/power/energy.html (10/1/2001).

Aluminum Association. 2001a. Aluminum Association: Recycling results. The Aluminum Association, Inc. http://www.aluminum.org (12/2/2001).

Aluminum Association. 2001b. Aluminum Association: Recycling results. The Aluminum Association, Inc. http://www.aluminum.org (2/28/2002).

APC. 2001. American Plastics Council. http://www.plasticsresource.com (11/28/2000).

API. 1996. Joint Association Survey on Drilling Costs. American Petroleum Institute, 1996, p. 92, American Petroleum Institute, Washington, D.C.

API. 1999. *Basic Petroleum Data Book.* Washington, D.C.: American Petroleum Institute.

APME. 2001. Plastics. Association of Plastics Manufacturers in Europe. http://www.ampe.org (2/12/2002).

ASE. 2001. Appliance standards and labeling. Alliance to save energy. http://www.ase.org/programs/applicances/_index.html (2/6/2002).

Ayres, R.U. 1997. Metals recycling: Economic and environmental implications. *Resources, Conservation and Recycling* 21: 145–173.

Bevington, R. and A. Rosenfeld. 1990. Energy for buildings and homes. *Scientific American* 263(3): 80–87.

Bioenergy. 1996. Washington's Corn Scam: Ethanol No., http://solstice.crest.org/renewables/bioenergy-list- (12/12/2001).

BP. 2001. *BP Statistical Review of World Energy 2001.* London: British Petroleum Corporate Communications Services. p. 41.

Busch, J.F. and A.K. Meier. 1986. Monitored performance of new, low-energy homes; updated results from the BECA—A data base. Lawrence Berkeley Laboratory, Berkeley, CA, LBL-18306.

Carmody, J., S. Selkowitz, and L. Heschong. 1996. *Residential Windows: A Guide to New Technologies and Energy Performance*. New York: W. Norton & Company, Inc.

Casper, M.E. (ed.). 1977. *Energy-Saving Techniques for the Food Industry.* Park Ridge, NJ: Noyes Data Corporation.

CBECS. 1995. Commercial Buildings Energy Consumption Survey (CBECS) 1995, www.eia.doe.gov/emeu/cbecs/char95/overview.html (2/7/2002).

Chahroudi, D. 1992. Weather panel architecture: A passive solar solution for cloudy climates. *Solar Today* 6: 17–20.

CMA. 1998. *U.S. Chemical Industry Statistical Handbook 1998.* Arlington, VA: Chemical Manufacturers Association.

Cohen, S.D., C.A. Goldman, and J.P. Harris. 1991. Measured energy savings and economics of retrofitting existing single-family homes: An update of the BECA-B database, Lawrence Berkeley Laboratory. Berkeley, CA. LBL 28147. 58 pp.

Collins, C. 2000. Prices under pressure. *Tire Business* 17: 3, 36.

Cummings, J.B., J. Tooley, N. Moyer, et al. 1990. Impacts of duct leakage on infiltration rates, space conditioning energy use, and peak electrical demand in Florida homes. In *Proceedings, ACEEE 1990 Summer Study on Energy Efficiency in Buildings*, Washington D.C.

Cureton, M. and D. Reed. 1995. *Washers, Dryers & Miscellaneous Appliances.* Snowmass, CO: Rocky Mountain Institute.

Dalzell, J.M. 1994. *Food Industry and the Environment: Practical Issues and Cost Implication.* London: Blackie Academic & Professional.

Danjczek, T. 2000. EAF steel makers help prevent loss of ferrous scrap. American Metal Market Electric Furnace Steel, Suppl. (Feb 20), 5A (2000). http://www.umi.com/proquest (10/10/2001).

Davis, J. and A. Swenson. 1998. Trends in energy use in commercial buildings—sixteen years of EIA's commercial buildings energy consumption survey. *American Council for Energy Efficient Economy* 4: 121–132.

Deffeyes, K.S. 2001. *Hubbert's Peak—The Impending World Oil Shortage.* Princeton, NJ: Princeton University Press.

DOE. 1995. Energy efficient lighting, consumer energy information: E.R.E.C. fact sheets. Energy Efficiency and Renewable Energy Network, http://www.eren.doe.gov/erec/factsheets/eelight.html (2/25/2002).

DOE. 1996. Energy consumption series: Residential lighting use and potential savings. September 1996, U.S. Department of Energy, Energy Information Administration, Office of Energy Markets and End Use. http://www.eia.doe.gov/emeu/lighting/ (4/3/2002).

DOE. 1997. *Annual Energy Outlook 1998 with Projections to 2020.* Washington, D.C.: U.S. Department of Energy.

DOE. 1999a. Growth in electricity use. Annual Energy Outlook. U.S. Department of Energy, Energy Information Administration, 1999.

DOE. 1999b. Renewable energy 1998: Issues and trends. U.S. Department of Energy, Energy Information Administration, 1999. www.osti.gov/servlets/purl/329505-Nyp50Z/webviewable/329505.pdf (12/7/2001).

DOE. 2000a. Annual Energy Outlook 2001, U.S. Department of Energy, Energy Information Administration. http://www.eia.doe.gov/oiaf/aeo/demand.html#trans (10/25/2002).

DOE. 2000b. Annual Energy Review, 2000. U.S. Department of Energy, http://www.eia.doe.gov/emeu/aer/contents.html (2/7/2002).

DOE. 2000c. *Retail Sales of Electricity, Revenue and Average Revenue per Kilowatthour by U.S. Electric Utilities to Ultimate Consumers by Census Division, and State, 1999–2000, Electric Power Annual 2000.* Vol. 1 (Tables A22–A23.) U.S. Department of Energy. http://www.eia.doe.gov/cneeaf/electricity/epav1/ (4/3/2002).

DOE. 2000d. Annual Energy Outlook 2000. U.S. Department of Energy, Energy Information Administration. December, 2000. DOE/EIA-0383 (2000).

DOE. 2000e. Energy and environmental profile of the U.S. chemical industry. U.S. Department of Energy, Office of Industrial Technology, May 2000.

DOE. 2000f. Energy use in the U.S. steel opportunities. U.S. Department of Energy. Office of Industrial Technologies. September 2000. http://www.oit.doe.gov (1/28/2002).

DOE. 2001a. United States Department of Energy, Energy Information Agency, Oct. 3, 2001, Energy in the United States 1635-2000, http://www.eia.doe.gov/emeu/aer/eh/petro.html (10/25/2001).

DOE. 2001b. Country analysis brief—United States of America. United States Department of Energy, Energy Information Administration, August 28, 2001. http://www.eia.doe.gov/emeu/cabs/usa.html (10/25/2001).

DOE. 2001c. Annual Energy Outlook 2001. Energy Information Agency. http://www.eia.doe.gov/oiaf/aeo/demand.html#trans (10/25/2001).

DOE. 2001d. Market trends—Energy demand, Annual Energy Outlook 2001. U.S. Department of Energy. http://www.eia.doe.gov/oiaf/aeo/demand.html#resi (2/7/2002).

DOE. 2001e. Aluminum industry analysis brief. United States Department of Energy, Energy Information Administration. August 31, 2000. http://www.eia.doe.gov/emeu/mecs/iab/aluminum/index.html (10/25/2002).

DOE. 2001f. Steel industry analysis brief. United States Department of Energy, Energy Information Administration. May 5, 2000. http://www.eia.doe.gov/emeu/mecs/iab/steel/index.html (10/24/2001).

DOE. 2001g. Plastics manufacturing through recovered post-consumer good. U.S. Department of Energy. Office of Industrial Technologies. http://www.oit.doe.gov/nice3 (2/12/2002).

DOE. 2001h. Use of recovered plastics in durable goods manufacturing. U.S. Department of Energy. Office of Industrial Technologies. http://www.oit.doe.gov/nice3 (2/12/2002).

DOE. 2002a. Refrigerators. Washington, D.C. http://www.eren.doe.gov/buildings/consumer_information.refrig/index.html (1/20/2002).

DOE. 2002b. Clothes washers. Washington, D.C. http://www.eren.doe.gov/buildings/consumer_information/clotheswashers/index.html (1/20/2002).

DOE. 2002c. Why buy an energy efficient diswasher? Washington, D.C. http://www.eren.doe.gov/buildings/consumer_ information/dishwash/dishwhy.html (1/20/2002).

DOE. 2002d. About DOE's Appliance Standards Program. Washington, D.C. http://www.eren.doe.gov/bulidings/consumer_information/ (2/28/2002).

DOE. 2002e. Electric elasticities. Washington, D.C. http://www.eia.doe.gov/oiaf/issues/building sector.html#cpe (1/20/2002).

DOE. 2002f. Annual electricity consumption for lighting. U.S. Department of Energy. http://www.eia.doe.gov/emeu/lighting/tab4_9.html (4/16/2002).

DOE/OBT. 1999. Technology fact sheet: Air sealing: Seal leaks and save energy! U.S. Department of Energy, Office of Building Technology, State, and Community Programs, November 1999. Southface Energy Institute and the Oak Ridge National Laboratory. DOE/G010099-767.

Doering, O.C. 1980. Accounting for energy in farm machinery and buildings. In D. Pimentel (ed.), *Handbook of Energy Utilization in Agriculture*, pp. 9–14. Boca Rotan, FL: CRC Press.

Duncan, R.C. 2001. World energy production, population growth, and the road to the Olduvai Gorge. *Population and Environment* 22(5): 503–522.

Duncan, R.C. and W. Youngquist. 1999. Encircling the peak of world oil production. *Natural Resources Research* 8(3): 219–232.

EELA. 1999. 25 Lighting facts. Energy Efficient Lighting Association, www.energywise.co.nz/content/EW_news/62june99/62eela.htm (2/7/2002).

EPA. 1995. Profile of the rubber and plastics industry. EPA. Office of Compliance Sector, September 1995. http://www.epa.gov (1/10/2001).

EP Rubber. 2000. *Chemical Market Reporter* 257: 41.

Facts at a Glance. 1999. The benefits of recycling: A compendium of facts. http://www.ciwmb.ca.gov/Boardinfo/Facts/Recycle.html (3/14/2002).

Florman, M. 1991. Warm house/cool house: A money-saving guide to energy use in your home. Lawrence Berkeley National Laboratory, Consumers Union of the United States. Lawrence Berkeley National Laboratory.

Forest, R. 1991. Transparent insulation: Student residences in Glasgow. In A.A.M. Sayigh (ed.), *Energy Conservation in Buildings*, pp. 72–77. Oxford: Pergamon Press.

Frost, K., J. Eto, D. Arasteh, et al. 1996. The national energy requirements of residential windows in the U.S.: Today and tomorrow. In *Proceedings of the ACEEE 1996 Summer Study on Energy Efficiency in Buildings, Profiting from Energy Efficiency,* August 25–31. 1996, Asilomar, Pacific Grove, CA. LBNL-39692.

George, K.L., J. Gregerson, M. Shepard, et al. 1994. *Residential Appliances: Technology Atlas.* Boulder, CO: E Source, Inc.

Greene, D.L. and J. DeCicco. 2000. Engineering-economic analyses of automotive fuel economy potential in the United States. (Dec. 6, 2000). Oak Ridge National Laboratory Center for Transportation Analysis. http://www-cta.ornl.gov/Publications/ORNL-TM-2000-26.pdf (10/1/2001).

Gunn, T.L. and B. Hannon. 1983. Energy conservation and recycling in the paper industry. *Resources and Energy* 5: 243–260.

Haase, H.P. 2001. Energy efficiency of out appliances in the household industry. In P. Bertoldi, A. Ricci, and A. de Almeida (eds.), *Energy Efficiency in Household Appliances and Lighting*, pp. 9–11. Berlin: Springer.

Hafemeister, D. and L. Wall, 1991. Energy conservation in buildings and appliances. In R. Howes and A. Fainberg (eds.), *The Energy Source Book: A Guide to Technology, Resources, and Policy*, pp. 48–56. New York: American Institute of Physics.

Hamilton, K. 2001. U.S. Government lavishes welfare on oil companies to deplete natural resources. http://www/progress.org./achchieve/cwoil.htm (9/27/2001).

Harris, J. and Johnson, F. 2000. Potential energy cost and CO_2 savings from energy efficient government purchasing. http://www.dc.lbl.gov/~harris/downloads/Government%20Purchasing.pdf (8/20/07).

Heede, R., O. Bailey, L. Baynham, et al. 1995. *Homemade Money: How to Save Energy Dollars in Your Home.* Amherst, NH: Bick House Publishing Company.

International Aluminum Institute. 2001. Aluminum energy recycling. http://www.nicholsal.com/welcome/nawelcome.html (3/14/2002).

IEA. 2000. International Energy Agency. Washington, D.C.: USDOE.

ITRA. 2001. Retreading rubber tires. International Tire and Rubber Association, http://www.itra.com (11/29/2001).

Jennings, J., R. Brown, M. Moezzi, et al. 1997. Residential lighting: The data to date. *Journal of the Illuminating Engineering Society* 26(2): 129–138. http://eetd.lbl.gov/btp/papers/38454.pdf (2/7/2002).

Jones, K.P. 2001. Rubber and the environment. International Rubber Research and Development Board. http://www.irrdb.org/property/green.html (4/12/2001).

Kilgore, W.C. 1994. Reducing home heating and cooling costs. DOE EIA Report # SR/EMEU/94. http://tonto.eia.doe.gov/ftproot/service/emeu9401.pdf (7/7/2002).

Koomey, J.G., S.A. Mahler, C.A. Webber, et al. 1998. Projected regional impacts of appliance efficiency standards for the U.S. residential sector. No. LBNL-355111. Energy Analysis Program, Energy and Environment Division, Ernest Orlando Lawrence Berkeley National Laboratory.

Koplow, D.N. 1993. *Federal Energy Subsidies: Energy, Environmental, and Fiscal Impacts.* Washington, D.C.: Alliance to Save Energy.

Kubo, T., H. Sachs, and S. Nadel. 2001. Opportunities for new appliance and equipment efficiency standards: Energy and economics savings beyond current standards programs. American Council for an Energy Efficient Economy, September 2001. http://aceee.org/energy/a016full.pdf (2/7/2002).

Laherrere, J. 2001. Estimates of oil reserves. IISA – International Worldshop. 41 pp.

Latta, R. 2000. Trends in residential air-conditioning usage from 1978 to 1997, Energy Information Agency, U.S. Department of Energy. http://www.eia.doe.gov/emeu/consumptionbriefs/recs/actrends/recs_ac_trends.html (8/72001).

LBNL. 1995. Energy star efficiency. Lawrence Berkeley National Laboratory. LBNL Report # LBNL-37383. http://endues.lbl.gov/Info/LBNL-37383.pdf (3/3/2002).

LBNL. 2000. Energy performance of buildings. Indoor Environment Department. Environmental Energy Technologies Division. Aerosol based duct sealing technology, Lawrence Berkeley National Laboratory. http://epb1.lbl.gov/aerosol/index.html (2/28/2002).

Levine, M.D., L. Price, N. Martin, et al. 1996. Energy and energy efficiency in buildings: A global analysis. *ACEEE Summer Study on Energy Efficiency in Buildings.* pp. 141–158.

MacKenzie, J.J. 1996. *Oil as a Finite Resource: When is Global Production Likely to Peak?* Washington, D.C.: World Resources Institute.

Mackinac. 2001. Natural gas price elasticity. Mackinac Center for Public Policy, Policy Research. http://www/mackinac.org/1247 No (2/28/2002).

Martin, N., E. Worrell, M. Ruth, et al. 2000a. Energy efficiency and renewable energy network. http://www.eren.doe.gov/EE/industry.html (2/12/2002).

Martin, N., E. Worrell, M. Ruth, et al. 2000b. Emerging energy-efficient industrial technologies. LBNL-46990, October 2000.

Matson, A.P., R. Naylor, and I. Ortiz-Monasterio. 1998. Integration of environmental, agronomic, and economic aspects of fertilizer management. *Science* 280(5360): 112–115.

M. Energy Rev. 2001. *Monthly Energy Review*, December 2001.

Merriss, J. 2001. *A Brief Reference on Fuel Costs and Fuel Price Elasticity.* Vol. 5, Issue 1, Oregon Department of Transportation, Policy Section.

Mintz, N.M. and A.D. Vyuas. 1991. *Forecast of Transportation Energy Demand through the Year 2010.* Chicago, IL: Argonne National Laboratory.

Mortier, J.M. 1997. Energy consumption of household appliances. In P. Bertoldi, A. Ricci and B.H. Wajer (eds.), *Energy Efficiency in Household Appliances,* pp. 17–21. Berlin: Springer-Verlag.

Nadel, S. 1997. Appliance energy efficiency: Opportunities, barriers and policy solutions. In P. Bertoldi, A. Ricci and B.H. Wajer (eds.), *Energy Efficiency in Household Appliances,* pp. 22–37. Berlin: Springer-Verlag.

NAIMA. 1996. Green and competitive: Energy, environmental and economic benefits of fiber glass and mineral wool insulation products. Energy Conservation Management, Inc.; The Alliance to Save Energy, and Barakat & Chamberlin, Inc. http://www.naima.org/updates/green.html (6/14/1996).

NAS. 2001. *Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards.* National Academy of Sciences, National Research Council Transportation Research Board (Unknown). National Academy Press. http://books.nap.edu/books/0309076013/html/index.html (10/25/2001).

Nehring, R. 1981. *The Discovery of Significant Oil and Gas Fields in the United States.* Santa Monica, CA: Rand Corporation.

NLB. 2001. Huge electrical energy savings immediately and inexpensively attainable, without sacrifice. National Lighting Bureau. June 5, 2001. http://www.nlb.news/index.html#12 (5/3/2002).

NTIS. 2001. Drying hardwood lumber. United States Forest Products Laboratory, 2001. NTIS PB2001-101263.

Okos, M., N. Rao, S. Drecher, et al. 1998. *Energy Use in the Food Industry.* Washington, D.C.: American Council for an Energy-Efficient Economy.

ORNL. 2000. *Transportation Energy Book*, 20th edition, ORNAL – 6959. Oak Ridge, TN: Oak Ridge National Laboratory.

OTA. 1992. *Building Energy Efficiency.* U.S. Congress, Office of Technology Assessment, OTA-E-518, Washington, D.C.: U.S. Government Printing Office, May 1992.

OTA. 1994. Saving energy in U.S. transportation. U.S. Congress, Office of Technology Assessment. OTA-ETI-589.

Pimentel, D. 1993. Environmental and economic benefits of sustainable agriculture. In M.A. Paoletti, T. Napier and O. Ferro (eds.), *Socio-Economic and Policy Issues for Sustainable Farming Systems,* pp. 5–20. Padova, Italy: Cooperativa Amicizia S.r.l.

Pimentel, D. 2001. The limitations of biomass energy. In *Encyclopedia on Physical Science and Technology,* pp. 159–171. San Diego, CA: Academic Press.

Pimentel, D. and M. Pimentel. 1996. *Food, Energy and Society.* Niwot, CO: Colorado University Press.

Pimentel, D., C. Harvey, P. Resosudarmo, et al. 1995. Environmental and economic costs of soil erosion and conservation benefits. *Science* 267: 1117–1123.

Pimentel, D., R. Doughty, C. Carothers, et al. 2002a. Energy and economic inputs in crop production: Comparison of developed and developing countries. In R. Lal, D. Hansen, N. Uphoff, et al. (eds.), *Food Security and Environmental Quality in the Developing World,* pp. 129–151. Boca Raton, FL: CRC Press.

Pimentel, D., M. Hertz, M. Glickstein, et al. 2002b. Renewable energy: Current and potential issues. *Bioscience* 52(12): 1111–1120.

Plastics Energy. 2002. http://www.plasticsindustry.org/outreach/energy.html (3/27/2002).

PNNL. 1994. Brief characterizations of the top 50 U.S. commodity chemicals. Pacific Northwest National Laboratory, 1994.

PNNL. 1995. Top 50 chemicals: Impact of catalytic process limitations on energy, environment, and economics. Pacific Northwest National Laboratory, 1995.

Reay, D. 1999. Learning from experiences with compact heat exchangers. CADDET Analyses Series, No. 25. Northampton, UK: IEA-CADDET, 1999.

RECS. 1995. Residential Energy Consumption Survey (RECS) 1995. http://www.eia.doe.gov/emeu/recs/recs1c.html (2/7/2002).

Reuters. 2001. Non-polluting ethanol increases demand for blending with gasoline. December 12, 2001. http:www.climateark.org/articles/2001/4th/nonpetha.html (3/4/2002).

RMA. 2001. Rubber Manufacturers Association, http://www.rma.org (11/29/2001).

RMI. 1994. Home energy brief #1—Lighting. Rocky Mountain Institute. http://www.rmi.org/images/other/E-HEB-Lighting.pdf (4/3/2002).

Romm, J.J. 2002. Cool companies. http://www.cool-companies.org/proven (3/5/2002).

Roos, A. and B. Karlsson. 1994. Optical and thermal characterization of multiple glazed windows with low U-values. *Solar Energy* 52(4): 315–325.

Sanchez, M.C., J.G. Koomey, M.M. Moezzi, et al. 1998. *Proceedings of the 1998 ACEEE Summer Study of Energy Efficiency Buildings*, August 1998.

Selke, S.E. 1994. Packaging options. In J.M. Dalzell (ed.), *Food Industry and the Environment: Practical Issues and Cost Implications,* pp. 283–317. London: Blackie Academic & Professional.

Sheahen, T.P. and J.F. Ryan. 1983. Technology transfer into capital-intensive industry: The paper industry by the year 2000. *Journal of Technology Transfer* 7(2): 69–84.

Sherman, M. 2001. Billions of lost energy leaking out of home heating and cooling products. Science Beat, Lawrence Berkeley Laboratory. http://www.lbl.gov/Science-Articles/Archive/leakyducts-billions.html (3/5/2002).

Simonsen, H.I., M.F. Davy, and G.E McBride. 1995. R&D opportunities for improvement in energy efficiency to the year 2010—an overview. *Pulp and Paper Canada* 96(6): 45–49.

Socolow, R. 1999. Nitrogen management and the future of food: Lessons from the management of energy and carbon. *Proceedings of the National Academy of Sciences USA* 96(11): 6001–6008.

Socolow, R.H. (ed.). 1978. The twin rivers program on energy conservation in housing highlights and conclusions. In *Saving Energy in the Home: Princeton's Experiments at Twin Rivers.* Cambridge, MA: Ballinger Publishing Company.

SRI. 2001. Steel recycling institute. Fact Sheet, http://www.recycle-steel.org/fact/main.html (10/1/2001).

Statistics. 2000. Department of Transportation. Washington, D.C.

Stone, H. 2002. Population and sustainability. Manuscript. Rochester, NY, Xerox Corporation.

Sustainable Sources. 2002. Energy efficient appliances. Sustainable sources. http://www.greenbuilder.com/sourcesbook/EnergyEffAppliance.html (2/6/2002).

Thorne, J., T. Kubo, and S. Nadel. 2000. Staying cool: How energy-efficient air conditioners can prevent blackouts, cut pollution, and save money. Appliance Standards Awareness Project. American Council for an Energy-Efficient Economy the Alliance to Save Energy, and the Natural Resources Defense Council. Boston, MA. http://www.standardsasap.org/asapcool.pdf.

Troeh, F.R., J.A. Hobbs, and R.L. Donahue. 1991. *Soil and Water Conservation,* 2nd ed. Englewood Cliffs, NJ: Prentice Hall.

TTI. 2001. Urban mobility study. Texas Transportation Institute. http://mobillity.tamu.edu/2001/study/final_report.pdf (10/3/2001).

Turiel, I., B. Atkinson, P. Chan, et al. 2001. Energy and carbon impact of new U.S. fluorescent lamp ballast energy efficiency standards. In P. Bertoldi, A. Ricci and A. de Almeida (eds.), *Energy Efficiency in Household Appliances and Lighting,* pp. 355–366. Berlin: Springer.

Twiddell, J.W., C. Johnstone, B. Zuhdy, et al. 1994. Strathclyde University's passive solar, low-energy, residence with transparent insulation. *Solar Energy* 52(1): 85–109.

USBC. 2000. United States Census Bureau, QT-03 Profile of Selected Economic Characteristics: 2000. http://factfinder.census.gov/servlet/QTTable?ds_name=ACS_C2SS_ES_G00_&geo_id=01000US&qr_name=ACS_C2SS_EST_G00_QT03 (10/25/2001).

USBC. 2001. *Statistical Abstract of the United States 2000.* Washington, D.C.: U.S. Bureau of the Census, U.S. Government Printing Office.

USBTS. 2000. *National Transportation Statistics 2000.* Washington, D.C.: U.S. Bureau of Transportation.

USDA. 2001. *Agricultural Statistics.* Washington, D.C.: U.S. Department of Agriculture.

USDOT. 1999. Transportation Statistics Annual Report 1999. United States Department of Transportation, Bureau of Transportation Statistics. http://www.bts.gov/transtu/tsar/tsar1999/index.html (10/25/2001).

USEPA. 2001. Light-duty automotive technology and fuel economy trends: 1975 through 2001. Office of Transportation and Air Quality, United States Environmental Protection Agency. http://www.epa.gov/otaq/cert/mpg/fetrends/r01008.pdf (10/25/2001).

Walshe, N.M.A. 1994. Energy conservation and the cost benefits to the food industry. In J.M. Dalzell (ed.), *Food Industry and the Environment: Practical Issues and Cost Implications,* pp. 76–105. London: Blackie Academic & Professional.

Wilson, A. and J. Morrill. 1999. *Consumer Guide to Home Energy Savings.* Washington, D.C.: American Council for an Energy-Efficient Economy.

Wilson, G.C. 1999. Clinton: Build trucks that save buck. *National Journal* 31(45): 3268–3269.

Wittwer, V., W. Platzer, and M. Rommell. 1991. Transparent insulation: An innovative European technology holds promise as one route to more efficient solar buildings and collectors. *Solar Today* 5: 20–22.

Worrell, E., N. Martin, and L. Price. 1999. Energy efficiency and carbon dioxide emissions reduction opportunities in the U.S. iron and steel sector. Lawrence Berkeley National Laboratory. LBNL-41724. July 1999.

Worrell, E., D. Phylipsen, D. Einstein, et al. 2000. Energy use and energy intensity of the U.S. chemical industry, LBNL-44314, April 2000.

Youngquist, W. 1997. *GeoDestinies: The Inevitable Control of Earth Resources over Nations and Individuals.* Portland, OR: National Book Company.

23 Summing Up: Options and Solutions

Tough questions about conservation of natural resources, development of alternative energy resources, desired standards of living, types of diet, and optimum populations size must be answered. All require decisive action.

The foremost question is how humans will be able to provide a nutritionally adequate diet for a world population expected to be more than 13 billion by 2055.

Food security for all is dependent on and interrelated with many factors within the vast human social and ecological system. Fundamentally, it depends upon human population numbers and the standard of living those humans desire. Environmental resources such as cropland, water, climate, and fossil energy for fertilizers and irrigation influence the outcome. The food supply is also affected by crop losses to pests, availability of labor, environmental pollution, and the health and lifestyle of the people. Distribution systems and the social organization of families and countries play a role in the solution.

FUTURE FOOD NEEDS

For about a million years, the human population growth rate was slow, averaging only about 0.001% per year. During that long period of time, the world population numbered less than 10 million (Keyfitz, 1976). Growth in human population numbers began to escalate about 10,000 years ago, when agriculture was first initiated. Rapid population growth, however, only started after the year 1700, when it accelerated to today's rate of 1.2% per year, about 1200 times the historical rate of 0.001% (NAS, 1975; Keyfitz, 1976; PRB, 2004). World population now stands at 6.5 billion and is expanding at a quarter million persons per day. Unless unforeseen factors intervene, it will reach more than 13 billion by 2055. Growth is not expected to end until after the year 2100.

The rapid growth in the world population has already resulted in an increased need for food. Estimates are that today 3.7 billion people, or more than half of the world population, are seriously malnourished (WHO, 2004).

POPULATION HEALTH

Rapid growth in the world population coincided with the exponential growth in the use of fossil fuels (Figure 23.1). Some of this energy has been used to promote public health, control disease, and increase food production for the ever-growing world population. The control of typhoid disease, for example, was achieved by improving

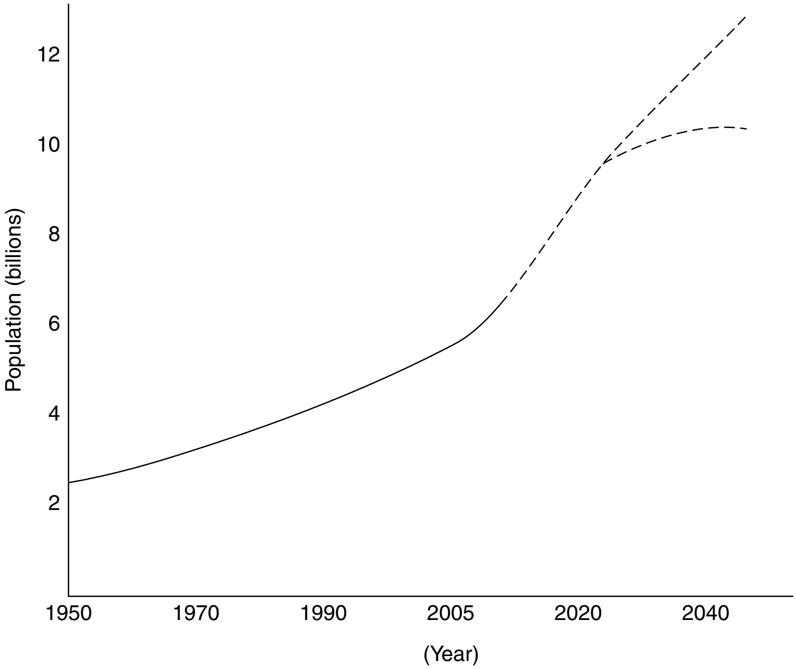

FIGURE 23.1 World population growth and fossil energy use (——) and projected (---) future trends for each. (Environmental Fund, 1979; Linden, 1980; USBC, 1994; PRB, 2006.)

water purification, which required large energy expenditures (Audy, 1964). The program for eradicating malaria-carrying mosquitoes required the application of DDT and other insecticides. Producing these insecticides used substantial quantities of energy (Audy, 1964).

Reduction in death rates through effective disease control has been followed by substantial increases in population growth rates. For example, in Sri Lanka (Ceylon), after spraying mosquitoes with DDT, the death rate fell from 20/1000 in 1946 to only 14/1000 in 1947 (PEP, 1955), and population growth rates concurrently increased. A similar dramatic reduction in death rate occurred after DDT was used on the island of Mauritius, where death rates fell from 27 to 15/1000 in 1 year, and population growth rates increased from about 5–35 per 1000 (Figure 23.2).

Historical evidence documents many similar occurrences in nations where public health technology improved sanitary practices and medical supplies significantly reduced death rates (Corsa and Oakley, 1971). The effective control of human diseases, coupled with increased food production, has contributed significantly to rapid population growth. Unfortunately, the immediate increase in family size and explosive population increase in cities, towns, and villages all too often overwhelms existing food, education, health, and social systems.

The presence of some chronic diseases also increases the need for food. For example, when a person is ill with diarrhea or malaria or is infested with a parasite such as hookworms, anywhere from 5% to 20% of the individual's energy intake

FIGURE 23.2 Population growth rate on Mauritius from 1920 to 1970. From 1920 to 1945 the growth rate was about 5 per 1000. After malaria control, in 1945, the growth rate exploded to about 35 per 1000 and has since very slowly declined. After 25 years the rate of increase is still nearly four times the 1920–1945 level. (Pimentel and Pimentel, 1979.)

is expended to offset the illness. With malaria, hookworms, and amebic dysentery, the parasites remove blood and nutrients and reduce the individual's ability to make effective use of his food.

FOOD LOSSES

Significant quantities of our food supply are lost to insects, plant pathogens, weeds, birds, rodents, and other pests. World crop losses due to pest infestation are estimated to be about 40% (Pimentel, 1997). These losses include destruction by insects (15%), plant pathogens (12%), weeds (12%), and mammals and birds (1%). Although mammal and bird losses are more severe in the tropics and subtropics than in the temperate regions, they are still low compared to those attributed to insects, pathogens, and weeds.

In addition, available evidence tends to suggest that some Green Revolution technologies have intensified losses to pests (I. N. Oka, Bogor Food Research Institute, Indonesia, personal communication, 1991). Some of the new high-yielding crop varieties exhibit greater susceptibility to some pests than do traditional varieties. In the past, farmers saved seeds from those individual plants that survived and yielded best under local cultural conditions and planted them in subsequent years. These genotypes were naturally resistant to pest insects and plant pathogens and competitive with weeds. In this way, farmers developed genotypes that grew best in their localities.

The newly developed grain varieties have more genetic uniformity, and this can become a distinct disadvantage when the variety is planted over large areas in a new environment. Such plantings provide an ideal ecological environment in which the plant pathogens can evolve highly destructive genotypes (I. N. Oka, Bogor Food Research Institute, Indonesia, personal communication, 1991). Concurrently, programs have been developed for multiple cropping in an effort to increase food supplies from limited land resources. This type of continuous crop culture has resulted in increased pest outbreaks. Higher crop losses to pest damage mean lower yields and less food.

Not all losses occur during the growing season; substantial postharvest losses occur. These are estimated to range from 10% in the United States to a high of 25% in many developing countries. The major pests that destroy harvested foods are microbes, insects, and rodents. When postharvest losses are added to preharvest losses, total food losses due to pests rise to an estimated 52%. Thus, pests destroy more than half of the potential world food supply. We cannot afford a loss of such magnitude when faced with an increasing need for food to feed the growing world population.

STRATEGIES FOR MEETING FOOD NEEDS

Two-thirds of the world's people consume primarily a vegetarian-type diet. These individuals eat about 200 kg of grain products yearly. They consume this grain directly and eat little food of animal origin. In contrast, the remaining one-third of the world's people, including those living in industrial countries such as the United States, consumes about 360 kg of animal food products yearly. To produce this amount of animal food in the United States, about 665 kg of grain per person are raised and then fed to animals.

Livestock, including poultry, in the United States alone number 9 billion and outweigh the human population by more than five times. Worldwide there are an estimated 30 billion livestock. These animals graze on about 30% of the world land area.

To increase the production of animal protein, the process must be made more efficient than it has been in the past. This is especially relevant to livestock production. Overgrazing should be prevented and more productive pasture plant species developed and cultured. Applications of limited amounts of livestock manure and perhaps fertilizers would increase forage yields. The annual supply of animal protein could be increased to about 50 million tons by the year 2050. This increase, however, would not be sufficient to maintain the present protein intake of 64 g per person per day for the world population, which in the meantime will also have increased substantially.

Some estimates report that the fishery harvest is about 95 million tons. This is probably the maximum yield, considering the serious overfishing problems that already exist. In addition, fish production is energy intensive; this energy has been and will continue to be a constraint on its expansion.

One way to increase food supplies is for humans to become more vegetarian in their eating habits. Annually, an estimated 40 million tons of grain protein suitable for human consumption are fed to the world's livestock. This represents 34% more protein that would be available as food for the world population if it was not cycled through livestock.

If the protein currently fed to livestock were instead fed directly to humans, then more food grains would be available to the world population. Assuming that improved management of livestock pasture and rangeland yielded an additional 25 million tons of livestock protein, then the increases needed in the following crops over a 20-year period would be: cereals, 41%; legumes, 20%; and other plant proteins, 50%. It is doubtful that these increases can be achieved. However, increased yields in plant crop production are more easily achieved than increases in animal production. Nevertheless, just as livestock production is vital to humans today, it will be important to humans in the future. Cattle, sheep, and goats will continue to be of value because they convert grasses and shrubs on pastures and rangeland into food suitable for humans. Without livestock, humans cannot make use of this type of vegetation on marginal lands.

ENERGY NEEDS IN FOOD PRODUCTION

In past decades humans did not have to concern themselves about fossil fuel supplies, because relatively inexpensive and ample supplies were available. Such will not be the case in the twenty-first century. An estimated 19% of the fossil energy consumed in the United States is used in the food production system. This 19% may seem neither large nor important when considered as a portion of the total U.S. energy expenditure, but compared to that of other nations (especially developing countries) it is extremely large. It amounts to more than twice the total per capita fossil use in Asia and about four times that in Africa (Figure 1.3).

The following analysis may help clarify the relationships of fossil fuel supplies to production of food supplies. The total energy used annually in the United States for food production, processing, distribution, and preparation is about 1500 L of oil per capita per year. Using U.S. agricultural technology to feed the present world population of 6.5 billion, a high protein/calorie diet for 1 year would require the equivalent of 9000×10^9 L of fuel annually.

Another way to understand the dependency of food production on fossil energy is to calculate how long it would take to deplete the known world reserve of petroleum if a high protein/calorie diet, produced using U.S. agricultural technologies, were fed to the entire world population. The known world oil reserves have been estimated to be 90×10^{12} L, so if we assume that 75% of raw oil can be converted to fuel, this would provide a useable reserve of 67×10^{12} L of oil. Assuming that oil were the only source of energy for food production and that all known oil reserves were used solely for food production, the reserves would last a mere 7 years from today. This estimate is based on a hypothetical stabilized population of 5.5 billion. The reality is that each day an additional quarter million new mouths must be fed.

How then can food supply and energy expenditures be balanced against a growing world population? Even tripling the food supply in the next 40 years would just about meet the basic food needs of the 11 billion people who will inhabit the Earth at that time. Doing so would require about a 10-fold increase in the total quantity of energy expended in food production. The large energy input per increment increase in food is needed to overcome the incremental decline in crop yields caused by erosion and pest damage.

One practical way to increase food supplies with minimal increase in fossil energy inputs is for the world population as a whole to consume more plant foods. This diet modification would reduce energy expenditures and increase food supplies, because less food suitable for human consumption would be fed to livestock. With livestock, roughly 25 cal of increased energy is needed to obtain 1 cal of food.

LAND CONSTRAINTS

Feeding a population of more than 6.5 billion a high protein/calorie diet using U.S. agricultural technology would require large areas of arable land. This will be the case even if only plant production is to be increased. Thus, it is important to know how much arable land now is available for use in agricultural production.

The United States, with a current population of 300 million people, has about 160 million ha planted to crops. This averages out to 0.5 ha/person. However, the cropland needed per American is only about 0.4, because 20% of our present crop yield is exported.

Worldwide, about 1.5 billion ha of arable land now exist for crops. Based on the present population of 6.5 billion, this averages out to be only 0.23 ha/person. Therefore, if at least 0.50 ha/person is needed to produce a U.S-type diet, there is not sufficient arable land, even with the addition of energy resources and other technology, to feed the rest of the world a U.S.-type diet.

In some regions it may be possible to bring some poor land into production. Best estimates are that cropland resources might be doubled to 3 billion with great cost, using large amounts of energy for fertilizers and other inputs. This increase in cropland would necessitate cutting down most forests and converting some pasturelands to cropland. Both changes would have negative impacts on biodiversity and production of needed forest products. Also, forest removal increases erosion, flooding, and other environmental damage.

Worldwide, more than 20 million ha of agricultural land is abandoned annually because of soil erosion and salinization. During the past 40 years, about 30% of total world arable land has been abandoned because it was no longer productive. Loss of arable land is increasing because poor farmers worldwide have to burn crop residues and dung as fuel because firewood supplies are declining and fossil fuels are much too costly. It is expected that 750 million ha of cropland will be abandoned by 2050 because of severe degradation. This is extremely bad news; about half of the current arable land now in cultivation will be unsuitable for food production by the middle of the twenty-first century.

Wind and water erosion seriously reduce the productivity of land. In the United States, the rate of soil erosion is estimated at 10 tons/ha annually. The United States has already abandoned an estimated 100 million ha (Pimentel et al., 1995). At least one-third of the topsoil has been eroded from U.S. cropland during more than a century of farming. Iowa, which has some of the best soils in the United States, reportedly has lost half its topsoil after little more than 100 years of farming (Risser, 1981).

So far, the reduced productivity of U.S. cropland due to erosion has been offset by increased use of fertilizers, irrigation, and pesticides. The estimate is that about 50 L of oil equivalents per hectare are expended each year to offset cropland degradation. In developing countries, the rate of soil loss is more than twice that of the United States, an estimated 30–40 tons/ha/year (Pimentel, 1993). Therefore, based on what we presently know, both the amount of arable land available for crop production and the amounts of extra energy needed to put poor land into production are serious constraints on expansion of crop production.

WATER CONSTRAINTS

Water is the major limiting factor in crop production worldwide because all plants require enormous amounts of water for their growth. For example, a corn crop will transpire about 5 million L of water during the growing season. If this water has to be added by irrigation, approximately 10 million L of irrigation water must be applied. Another way of assessing water needs is to point out that 1000 L of water is necessary for the production of 1 kg of corn.

Indeed, agriculture is the major consumer of available water. In the United States, irrigated agriculture consumes (nonrecoverable) about 80% of the fresh water that is pumped, and the public and industry consume the remaining 20%. Worldwide, agriculture uses about 70% of the fresh water pumped.

Only about 17% of the world's cultivated land is now irrigated. In the arid lands, various sectors of the economy have conflicting demands for available water. Agriculture must compete with industry and public use of water, because the economic yields from agriculture per quantity of water used are far less than economic yields from industry. The public always needs water to drink and for other personal uses.

Expansion of irrigation is further limited because it requires large amounts of energy. About 20 million kcal of energy is needed to pump 10 million L of water from a depth of 30 m and irrigate by sprinkler system. This is more than three times the fossil energy input of 6 million kcal usually expended to produce 1 ha of corn. In addition, 13% more energy is required to maintain the irrigation equipment. These figures do not include the environmental costs of soil salinization or waterlogging often associated with irrigation.

High rainfall and the presence of too much water, or rapid water runoff, also cause serious environmental problems. The removal of forests and other vegetation, in particular on slopes, encourages water runoff and often results in serious flood damage to crops and pasture. In fact, environmental damages caused by floodwater, soil sediments, and related watershed damage are estimated to be about $6 billion per year.

CLIMATE

Climate has always determined the suitability of land for cultivation of crops. For this reason, changes in temperature and rainfall can be expected to influence food production and supplies. These two considerations must be evaluated on different time scales. Within any given decade, there are likely to occur irregularities in temperature and rainfall patterns that may either improve crop yields or inflict enormous damage to agricultural yields (e.g., the drought that occurred in the United States in 2005). However, long-term changes may have far more serious consequences. In particular, many scientists are concerned about global warming because of the greenhouse effect, which may affect agricultural production. The sensitivity of crops to temperature change is illustrated with corn. For example, a mere 0.6°C increase in temperature would lengthen the growing season by about 2 weeks and increases crop yields. However, global warming would also reduce the amount of water available for crop production. On balance, global warming would have a negative impact on agriculture.

The changes wrought by irregularities of climate patterns call attention to the interdependency of nations and the importance of cooperative planning. The effects of such irregularities also emphasize the need for the establishment of an international food reserve to offset years in which crop yields in the food-producing regions of the world are unexpectedly low.

ENVIRONMENTAL POLLUTION

Numerous wastes produced by agricultural production are considered pollutants. These include fertilizers, pesticides, livestock manure, exhaust gases from machinery, soil sediments, odors, dust, wastewater, and crop wastes. Pesticide use in the world totals 3.0 million tons, yet insects, plant pathogens, and weeds still destroy about 40% of all potential food in the world. However, pesticides are important, for without them food losses would rise to about 60%.

Pesticides, however, also cause serious public health and environmental problems. Worldwide, about 26 million human people a year suffer from pesticide poisoning, with about 220,000 fatalities. In the United States there are about 300,000 human pesticide poisonings per year with about 25 fatalities. In addition, there are as many as 10,000 cases of cancer associated with pesticide use. In addition, fish, honeybees, birds, and natural enemies are killed. The total environmental and health costs of using pesticides are estimated to be more than $11.3 billion per year (Pimentel, 2005).

On the world scene, pesticide use in agriculture has contaminated water with pesticides and exposed mosquito populations to insecticides. The result has been the development of high levels of resistance to insecticides worldwide and an explosion in the incidence of malaria, which is now difficult to control. The various environmental problems associated with pesticides appear to be increasing worldwide (Pimentel, 2005).

THE FUTURE

There is no single cause of the growing shortages of food, land, water, and energy or pollution of the environment, nor are there simple solutions. When all the world's resources and assets must be divided among an increasing number of people, each one has a smaller share, until there are insufficient amounts to go around.

At this point it is relevant to reconsider the biological law Malthus proposed: "First, that food is necessary to the existence of man. Secondly, that the passion between the sexes is necessary and will remain nearly in its present state.... Assuming then my postula are granted, I say that the power of population is definitely greater than the power of the Earth to produce sustenance for man." Malthus may not have been thinking about this aspect, but it is true that food production increases linearly, whereas the human population increases geometrically. Therefore, there is no biophysical way for food production to increase and stay with the growth of the human population. Even if population increase were not geometric, there are limits to the Earth's carrying capacity.

Perhaps Bertrand Russell (1961) best expressed the biological law related to population growth when he wrote: "Every living thing is a sort of imperialist seeking to transform as much as possible of its environment into itself and its seed." This law suggests that the human population will increase until food or some other basic need limits its survival and growth.

Although science and technology will help alleviate some of the future shortages, they cannot solve all the problems the world faces today. Science has been unable to solve many of the world's problems during the past 50 years, and with fewer resources that must be shared with more people, we have no reason to expect that biophysical limits can be overcome. For example, more, larger, and faster fishing vessels have not increased fish production; on the contrary, it is declining. Likewise, water flowing in the Colorado River now ceases to reach the Sea of Cortes. There is no technology that can double the flow of the Colorado or increase rainfall.

We remain optimists, for we see some signs that people are beginning to understand that resources are not unlimited and that a balance must be achieved between the basic needs of the human population and environmental resources, many of which are finite. This is the time to take action.

Above all else humans must control their numbers. This task is probably the most difficult one facing all of us today. If birth rates are to decline on a massive scale, parents must understand that having fewer children is in their own and their children's interest. This understanding can be achieved only if the direct costs of having children are increased and if socially acceptable substitutes for large families are developed. Within each country and each ecological system, difficult social changes must be encouraged in conjunction with policies that augment food supplies and improve health, education, and lifestyle.

What humans choose to do in the coming two decades will determine the kind of world the next generations will live in. Ultimately, it is up to each individual to reduce his or her reproductive rate. Clearly, if humans do not control their numbers, nature will do so through poverty, disease, and starvation.

REFERENCES

Audy, J.R. 1964. *Public Health and Medical Sciences in the Pacific—a Forty-Year Review.* Tenth Pacific Science Congress. Honolulu: University Press.

Corsa, L. and D. Oakley. 1971. Consequences of population growth for health services in less developed countries—an initial appraisal. In National Academy of Sciences (ed.), *Rapid Population Growth*, pp. 368–402. Baltimore, MD: Johns Hopkins Press.

Environmental Fund. 1979. *World Population Estimates.* Washington, D.C.: The Environmental Fund.

Keyfitz, N. 1976. World resources and the world middle class. *Scientific American* 235: 28–35.

Linden, H.R. 1980. *1980 Assessment of the U.S. and World Energy Situation and Outlook.* Chicago, IL: Gas Research Institute.

National Academy of Sciences (NAS). 1975. *Population and Food: Crucial Issues.* Washington, D.C.: National Academy of Sciences.

Pimentel, D. (ed.). 1993. *World Soil Erosion and Conservation.* Cambridge, UK: Cambridge University Press.

Pimentel, D. (ed.). 1997. *Techniques for Reducing Pesticide Use: Environmental and Economic Benefits,* 444 pp. Chichester, UK: John Wiley & Sons.

Pimentel, D. 2005. Environmental and economic costs of the application of pesticides primarily in the United States. *Environment, Development and Sustainability* 7: 229–252.

Pimentel, D. and M. Pimentel. 1979. *Food, Energy and Society.* London: Edward Arnold.

Pimentel, D., C. Harvey, P. Resosudarmo, et al. 1995. Environmental and economic costs of soil erosion and conservation benefits. *Science* 267: 1117–1123.

Political and Economic Planning (PEP). 1955. *World Population and Resources.* London: Political and Economic Planning.

Population Reference Bureau (PRB). 2006. *2006 World Population Data Sheet.* Washington, D.C.: PRB, Inc.

Risser, J. 1981. A renewed threat of soil erosion: It's worse than the Dust Bowl. *Smithsonian* 11: 120–122, 124, 126–130.

Russell, B. 1961. *An Outline of Philosophy.* Cleveland, OH: World Publishing.

U.S. Bureau of the Census (USBC). 1994. *Statistical Abstract of the United States 1993.* U.S. Bureau of the Census. Washington, D.C.: U.S. Government Printing Office.

World Health Organization (WHO) 2004. http://www.unsystem.org/scn/Publications/AnnualMeeting/SCN31/SCN5Report.pdf (7/7/2005).

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