COMMITTEE V
The Human Food Chain

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ECOLOGICAL ASPECTS OF THE HUMAN FOOD CHAIN

by

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I. Introduction

Agricultural science could benefit from a holistic or integrated approach. A wide array of disciplines contribute to agricultural science, including plant and animal physiology, biochemistry, plant and animal genetics and breeding, agronomy, chemistry, physics, entomology, plant pathology, horticulture, pomology, animal husbandry, vegetable crops, economics, sociology, and others. Often the scientists in these disciplines conduct their own research and make their own ad hoc recommendations with little consideration given to the impact of their results on the agricultural system as a whole. For example, in plant breeding the prime focus was for increased yield with little attention given to insect pests. The breeders would employ insecticides to keep the insects off their test plots. In some cases, the result of this practice was to introduce crops to the farmer that were more susceptible to insect attack (Pradhan, 1971; Oka and Pimentel, 1976).

Numerous other examples exist of problems in agriculture being created because of the lack of an integrated discipline approach, but it is clear that a major breakthrough in agricultural research will be when this science becomes unified and the many disciplines start working together on the major problems facing agriculture. There is no question that the science of agriculture is highly complex, and it would be impossible to have all the relevant disciplines, say a dozen or more, working on the same agricultural problem. Two to four, however, is a reasonable number of disciplines working on the details of some food production problem. In addition to having several disciplines working on the same problem, it is essential that each individual investigator adopt a holistic perspective of the human food system. That is, the investigators should be continually considering the broad implications and interconnections of their investigations with other aspects of agriculture, society, and the environment while they are pursuing their research.

The objective of this paper will be to examine the ecological aspects of the human food chain with an aim of finding a unified view of the food system to help in developing a holistic approach in agriculture. The primary emphasis in developing this holistic perspective will be to focus on crop and livestock production, because the environmental and social effects are greater in production technology than with food processing, packaging, distribution, and preparation. If some unity of science for the ecology of the human food chain can be developed, I feel that this would improve the food supply for humans, improve resource productivity and sustainability, and protect the environment and human well being.

II. Ecological Systems and the Human Food Chain

The natural ecological system is a network of energy and mineral flows in which the major functional components are populations of plants, animals, and microorganisms. These organisms perform different specialized functions in the ecological system. All self-sufficient ecosystems consist of producers (plants), consumers (animals and microbes), and reducers or decomposers (microbes and animals) (Figure 1). Macro- and microscopic plants collect solar energy and convert it into chemical energy via photosynthesis. Plants 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; animals eat other animals. The decomposer organisms feed on both dead plants and animals and their wastes and recycle the mineral resources to be used again by plants. Thus, consumers, reducers, and decomposers all depend, directly and indirectly, on plants as their food source.

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 plant materials. About half of all species obtain their resources directly from living hosts (Pimentel, 1968; Price, 1975). The sugarcane plant worldwide, for example, has 1645 parasitic insect species (Strong et al., 1977) and at least 100 parasitic disease microorganisms (Martin et al., 1961). Oaks in the United States have over 500 known insect species and probably close to 1000 that feed on them (Packard, 1890; de Mesa, 1928; Opler, 1974). One of the major insect herbivore parasites of the oaks in the Northeast is the gypsy moth, which in turn has about 95 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 a living food resource is a dominant way of life in natural ecosystems.

Solar energy powers the total natural ecological system. Annually the total light energy reaching the earth is calculated to be about 714×10^{18} kcal (Rabson et al., 1977), but the amount of light energy or sunlight used by plants is relatively minute. The total light energy "fixed" by plants annually is estimated to be 400×10^{15} kcal. Of this an estimated 200×10^{15} kcal are fixed by ocean ecosystems (Bunt, 1975), and an estimated 200 x 10^{15} kcal are fixed by terrestrial ecosystems.[1/] Although terrestrial systems cover only 30% of the earth, they fix at least half of the light energy. The annual amount of energy fixed by the world's plants, however, amounts to less than 0.1% of the total sunlight energy reaching the earth (Whittaker and Likens, 1975). In general in natural ecosystems of the temperate zone an average of 14 x 10^9 kcal of sunlight reaches a hectare per year (Reifsnyder and Lull, 1965) and the net energy fixed by plants averages about 13 x 10^6 kcal/ha (less than 0.1%). Expressed as the dry weight of plant material biomass, an average yield is about 2,400 kg/ha per year, with yields ranging from near zero in some rock and desert areas to 10,000 kg/ha in some swamps and marshes (Whittaker and Likens, 1975). As indicated, the amount of light energy fixed by plants in an ecosystem depends on a great many factors including water, nutrients, temperature, and the species present.

Nutrients and recycling of minerals used in living organisms were mentioned, and these are a vital part of the functioning of natural ecological systems. Several chemical elements, including carbon, hydrogen, oxygen, nitrogen, phosphorus, potassium and calcium, are essential to all living organisms. Various biogeochemical cycles have evolved to insure that plants, animals, and microbes have suitable amounts of these vital chemical elements. Biogeochemical cycles both conserve the vital elements and keep them in circulation in the ecosystem. In addition the mortality

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[1/] The estimated 200 x 10^{15} kcal fixed by world terrestrial ecosystems is based on the calculated average light energy fixed by the U.S. ecosystem (Table 1). Our estimate of 400 x 10^{15} kcal of light energy fixed by world vegetation annually is less than previous estimates that range from 626 x 10^{15} kcal to 987 x 10^{15} kcal (Fogg, 1972; Lieth and Whittaker, 1975; Rodin et al., 1975; Boardman, 1977).

of living organisms keeps the vital elements in circulation enabling the system to evolve and adapt to new and changing environments.

These biogeochemical cycles themselves are a product of evolution in the living system. If the living system had not evolved a way of keeping the vital chemicals in circulation and conserving them for use in the biological system, it would have become extinct long ago.

Every organism, for example, 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, atmospheric nitrogen cannot be used directly but must be converted into nitrates, which is often accomplished by nitrogen-fixing bacteria and algae (Figure 2). Some of these bacteria have a mutualistic relationship with certain plants like legumes. Host plants develop nodules and other structures on their roots to protect and feed the bacteria. Some plants, for example, provide the associated bacteria carbohydrates and other nutrients. In turn, the bacteria fix nitrogen for their own use as well as for the legume plant.

Earlier it was mentioned that food dominates the structure and functioning of ecological systems and that most species live as parasites feeding on other living organisms. This relationship of parasites and hosts in ecosystems provides a functional interdependence in natural communities. Parasites depend on their hosts for food, thus from an ecological perspective, host conservation is vital for parasite survival.

There are many theories as to how host plants survive the attack of herbivore/parasite populations (Pimentel, 1987). It is my view that herbivore/parasite populations and plant populations coevolve and function interdependently to achieve a balanced food supply-demand economy. I propose 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, 1987). I also postulate that herbivore and other 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. Essential energy and mineral resources necessary for growth, maintenance, and reproduction account for most of the host's resources, whereas harvestable energy has to be a relatively small portion of host resources. This hypothesis suggests one reason why trees and other plants generally remain green and lush in nature and why herbivores and other parasites are relatively sparse in biomass, especially related to their food hosts.

III. Unifying Concept of Human and Natural Food Chains

The production of crops and livestock for the human food chain is governed by the same ecological principles that govern food chains in all natural ecological systems. Examining these principles suggests that perhaps a unifying concept can be developed for human and natural food chains by focusing on energy budget and flows in human and natural systems. We should be able to assess and measure plant productivity, land area, water, work and power, biological diversity, environmental quality and pollution, degradation of resources, and change and stress in ecosystems using energy budgets and flows.

Solar and Fossil Energy

Solar energy provides the fuel to power all agricultural and natural food systems. In natural systems, solar energy provides the total energy input whereas in agriculture solar energy provides from 80 to 95% of the total energy input. In agriculture, from 5 to 20% may be fossil energy (Pimentel and Pimentel, 1979; Stanhill, 1984). In the temperate region, about 14 x 10^9 kcal reach a hectare during the year (Reifsnyder and Lull, 1965). Approximately half or 7 x 10^9 kcal reaches a hectare of land during the summer 4-month growing season.

Under optimal conditions, a highly productive crop like corn can fix 1% of the solar energy reaching a hectare during the growing season (Pimentel, 1984). Half of this or about 0.5% is corn grain. If the calculations were to include the total solar energy reaching the land area, then only about 0.25% of the solar energy is converted into grain.

When wheat, cabbage, strawberries, and other less productive crops than corn are assessed, then only about 0.1% of the solar energy is fixed and harvested as food. This 0.1% is similar to the amount of solar energy fixed by all biomass in natural ecological systems (Pimentel et al., 1978a).

Although the amount of solar energy collected by natural plants and crop plants is small, solar energy is essential to the total life system including agriculture. With the amount of solar energy that is collected being relative small, it is clear that plants must conserve their resources carefully. They must use most or nearly all of their resources for their own growth, maintenance, and reproduction (Pimentel, 1987). Generally the plant hosts can give up relatively small amounts of their resources to feeding parasites and predators. A recent study reported that only about

7% of living plant biomass is consumed by herbivores/parasites during the growing season from natural plant hosts (Pimentel, 1987).

In agriculture, it is estimated that 37% of all potential harvested food material is lost due to pests despite the use of about 500,000 t of pesticides used annually in the United States plus all nonchemical controls in use (Pimentel and Levitan, 1986). If no pesticidal and nonchemical controls were employed, it is estimated that total potential food losses would average about 45% (Pimentel et al., 1978b). This suggests about 25% of the total solar energy fixed would be lost to pests, since the 45% does not include crop residues. In any case, the point can be made that crop plants are about 3 times more susceptible to loss of their resources to parasites (pests) than are natural plants. Natural plants lose an average of 7% of their biomass to attacking herbivores. This is not surprising when the ecological conditions of crop culture are considered.

Agriculture and Altering Ecological Systems

All ecological systems can be changed by manipulating the composition of species in the ecosystem and/or altering the nutrients and water availability and/or treating the ecosystem with some chemical toxicant like a pesticide. The goal in agriculture is to manipulate ecosystems to have these systems produce food crops and livestock desired for the human food chain. Often natural plant and animal species are replaced by certain crop species and livestock species. In addition, in many cases fertilizers, pesticides, irrigation, and other changes are made in the environment to improve the food yield per hectare for society. In all cases, altering natural ecosystems for human food production requires human labor and other renewable and/or fossil energy inputs. The general rule is that the more that the ecosystem is altered, the larger the total energy inputs from human and fossil sources (Pimentel, 1980; Stanhill, 1984).

The rule of energy inputs rising as the ecosystem is more intensely managed can be illustrated by raising corn by hand, using oxen, and using mechanization including fertilizers, pesticides, and irrigation. For example, producing corn in Mexico by hand using swidden or cut/burn agricultural technology requires only a laborer with an axe and a hoe (Table 2). The total energy input for the manpower is 4120 kcal per day. Corn production requires about 1140 hours (143 days), making the total manpower energy expended 589,160 kcal/ha. When the energy for making the axe and hoe and producing the seed is added, the total energy input needed to produce corn in Mexico with only manpower is about 642,390 kcal/ha. With the corn yield per hectare about 1940 kg or 6.9×10^6 kcal, the output/input ratio is about 11:1 (Table 2).

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 kcal of fossil fuel expended.

Again using data from Mexico about 200 hours of ox power are needed to produce one hectare of corn. Concurrently, the man-hours needed are reduced to about 380 hours (Table 3). Based on the fact that producing corn by hand in Mexico requires about 1140 hours per hectare, the 200 hours of ox power reduces the manpower input by about 760 hours (Tables 2 and 3). This means that under these farming conditions 1 hour of ox power replaced nearly 4 hours of manpower.

An ox produces 0.5-0.75 horsepower. One horsepower-hour of work, as mentioned, is equal to about 10 manpower-hours of work. Thus, 1 ox power-hour is equal to 5-7.5 manpower-hours of work. Hence, the 1 ox power-hour of work replaces about 4 hours of manpower (Table 2 and 3). This is slightly lower than the theoretical 0.5-0.75 horsepower-hour capacity of ox power.

Assuming that an ox consumes about 20,000 kcal/day in feed (Pimentel and Pimentel, 1979), and a man consumes about 4120 kcal/day, the man/ox combination requires more energy input than the man alone (Tables 2 and 3). It should be re-emphasized, however, that while man consumes mostly corn grain, the ox consumes mostly forage, which is unsuitable for human consumption.

The total energy input for the man/ox combination is about 770,250 kcal/ha, for an output/input ratio of about 4:1. This low ratio is due to reduced corn yield, which is less than half (about 940 kg/ha) the yield obtained by manpower alone (about 1940 kg/ha) (Table 2 and 3). One possible reason for this is that the corn was planted on bottomland that had been in corn production for several years. In all probability this meant the fertility of the soil on this bottomland was lower than that in the slash-and-burn farm areas. If manure and organic matter had been added to the soil each season, the corn yields might have equalled those of the slash-and-burn system. The man/ox hour inputs, however, would increase. These inputs are needed to gather, transport, and spread manure and organic matter.

The energetics of intensely managed corn production confirms that major alterations to the land area for crop production requires significantly more energy (Table 4). The expected changes include reduced manpower to only 10 hours per hectare or substantially less than 1144 hours in the hand system and 383 hours in the draft animal system (Tables 2, 3, and 4). Other inputs missing from the other two systems include heavy machinery, fuel, fertilizers, pesticides, irrigation, corn drying, electrical energy, and transport of these goods to the farm (Table 4).

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, or more than 40% of the total fossil energy inputs (Table 4). Machinery and fuel together total about 22% of the fossil energy input. Taken as a whole, about one-third of the energy inputs in U.S. corn production reduce man and animal power inputs, and about two-thirds increase corn productivity. All the inputs, however, alter the ecosystem much more than either the hand or draft animal systems (Tables 2, 3, and 4).

Similar to crop, the more intensely that livestock production systems are managed and the ecosystem manipulated for animal product production, the greater the energy input for the product output. For example, in producing feedlot beef in California it was calculated that 78 kcal of energy were required to produce 1 kcal of protein (Pimentel et al., 1975). Feedlot beef are confined in stalls and fed hay and concentrates carried to the animals. In contrast rangeland beef are confined to pastures and are allowed to obtain their own forage by grazing with minimal amounts of management. Thus, in Texas on relatively good pasture beef cattle were reported to produce 1 kcal of protein with an input of only about 10 kcal of fossil energy (Pimentel et al., 1975). Clearly, the intensity of management and change in the ecosystem was much less for the rangefed beef compared with the feedlot produced beef.

Biological Diversity and Energy Flow in Food Systems

Increasing the biological diversity of crop production systems can significantly increase the solar energy captured by the plants and raise the total amount of biomass produced including the food produced. This has been demonstrated producing corn with low fertilizer inputs versus employing a two species agroforestry system that included corn and a leguminous tree (Leucaena).

Corn production in the two systems was assumed to be carried out using draft ox-power of about 200 hrs/ha and human labor of 400 hrs/ha (Table 5). These inputs are typical of corn production using draft animals and human labor (Table 3). The only other inputs in these systems were a small amount of machinery (2.5 kg/ha) and seeds (15-21 kg/ha) (Table 5). The total energy input for producing corn by the low fertilizer input system was 1.7×10^6 kcal. Corn yield was assumed to be 1000 kg/ha, which is typical for such systems (Torres, 1984). Using the agroforestry system, one half of a hectare is planted to corn and the other half to the Leucaena tree. This design includes planting 2 rows of corn alternated with 2 rows of Leucaena. The corn in this agroforestry system is planted at twice the density of low input corn, thus the same amount of maize seed (15 kg) is used in this agroforestry system as in the low-fertilizer system.

Estimates are the yield of corn grain can be increased 50% from about 1000 kg/ha to about 1500 kg/ha employing the agroforestry technology (Table 5), because of the added nitrogen provided by the Leucaena trees (Rachie, 1983; Torres, 1984). The total energy input in this system was 1.9×10^6 kcal. Corn yield was increased to 1500 kg/ha, which is typical of this system (Torres, 1984).

The Leucaena is prevented from competing with the corn by cutting the Leucaena back to a stump of about 8 cm before the corn is planted. The biomass produced by the Leucaena is 4,500 kg/ha (Rachie, 1983). Of this total biomass, 2,500 kg of leaves and small twigs are worked into the soil for biological nitrogen and organic matter for soil and water conservation. The remaining 2,000 kg of Leucaena is harvested as stems for fuelwood for the farmer. The small stems 2-5 cm in diameter are preferred as a cooking fuel.

About two-thirds of the nitrogen in the Leucaena biomass is contained in the 2,500 kg of leaves and twigs, whereas only one-third of the nitrogen is in the 2,000 kg of stemwood harvested (Rachie, 1983). The quantity of nitrogen applied to the land via 2,500 kg of Leucaena is about 60 kg/ha. Each kilogram of nitrogen increases maize yields about 10 kg (Torres, 1984).

Thus the two species agroforestry system was significantly more productive than the single species corn monoculture. The two species system produced a total of 7,500 kg of total biomass or 3.5 times that in the corn monoculture of 2,000 kg (Table 5). The solar energy captured in the two species system was 6 times that in the corn monoculture (Table 5).

Economic and Social Indicators in the Food Chain

When energy flow assessments were first utilized in agriculture, some economists were unhappy with this measure and felt that another monetary system was being established (Ruttan, 1975). Instead, I viewed the use of energy flow as an advantage in assisting ecologists, economists, and others to measure economic and social benefits for the food chain. Fossil energy is an important input in agriculture and often accounts for more than two-thirds of the total production costs when the products derived from fossil fuels are assessed in the costs of production (Table 4).

Because energy is such an important and costly resource especially in intensive agriculture, it makes a good indicator of where technologies might be profitable to develop and reduce these costly inputs. For example, in Table 4 machinery and fertilizers are the two most costly inputs. If one were interested in reducing the economic costs of production as well as the energy inputs, then one would focus research on machinery and fertilizer inputs to reduce the economic and energy inputs in production.

In addition, energy budgets can be utilized to help in selecting nutrients and crops that might best be grown to provide society with their basic food needs in the most economic manner. For example, twice as much vitamin C can be produced by growing tomatoes than citrus using the same energy input (Pimentel, 1980; Lang, 1986). If one wanted to examine the vitamin C need plus other nutrients, then potatoes would be the crop to be selected if energy, economics, and nutrition were included in the multidisiplinary assessment. It is interesting to note that today potatoes provide about 20% of vitamin C in U.S. diets. This is equal to the amount of vitamin C obtained from citrus (USDA, 1986).

Energy input and output analyses play an important role in decisions by farmers to produce one crop over another in a particular environment. For example, in the north central region of the United States the soil and climate is favorable for corn, thus it is profitable for farmers in this region to make heavy investments in energy to produce corn. However, further west in the United States where rainfall is reduced farmers find it more profitable to invest in reduced energy inputs to produce wheat, which is lower yielding than corn (Pimentel, 1980; USDA, 1986).

Biomass energy is closely related to agriculture and competes for some of the same land (ERAB, 1981; Pimentel et al., 1984). When land requirements were assessed for the profitability of producing solar energy, it was found that producing electrical energy for a city of 100,000 people required 330,000 ha whereas supplying the same amount of electrical energy using hydropower required only 13,000 ha (Table 6). Thus, energy budgets can be helpful is assessing the use of land, water, and biological resources for the conversion of solar energy into electrical energy for society.

Clearly, we have demonstrated in this section that energy budgets and flow measurements can be extremely valuable in multidisciplinary investigations of the economic and social benefits of food production and the use of land, water, and biota for either food or solar energy production.

Degradation of Resources and Energy Budgets

When land is degraded by soil erosion, the United States and other nations in the world use energy in the form of fertilizers, irrigation, pesticides, and other inputs to offset soil degradation (Pimentel et al., 1987a). Soil degradation can be measured in terms of energy. For example, with an average erosion rate of 18 t/ha/yr over ten years, about 1.3 cm of soil is lost. This decreased soil depth would reduce corn yields about 8% on soils less then 30 cm in depth and is equivalent to a loss of 520 kg corn/ha/yr. Assuming this reduced yield can be offset by fertilizer and other production inputs, then about $20/ha/yr is required to offset reduced soil depth or about 478,000 kcal of energy.

In the example given above, the energy inputs for offsetting reduced soil depth due to erosion was given but this can be a misleading assessment because reduced soil depth is only a minor impact from soil erosion. However often assessments of the effect of erosion on crop productivity are based only on reduced soil depth (Craft et al., 1985; Crosson, 1985). In these studies that focus only on soil depth, corn yields are reported to decline less than 1% per centimeter of soil depth reduction in corn production (Craft et al., 1985). Thus, a loss of 18 t/ha/yr of soil, which removes about 1.3 mm of soil depth, would result in a reduced corn yield of less than 0.1%. Because this reduction in rooting depth and productivity is relatively minor, several studies have concluded that the costs of implementing certain soil conservation technologies are greater than the annual benefits they would produce (Shrader et al., 1963; Berglund and Michalson, 1981; Crosson and Stout, 1983; Mueller et al., 1985).

If, however, the total effects of erosion are measured instead of only by soil depth, then from 15 to 30% reductions in crop yields result from moderate to severe erosion (Battiston et al., 1985; Schertz et al., 1985; McDaniel and Hajek, 1985). Thus, the total benefits of soil conservation that prevent losses of water, nutrients, and organic matter are significant (Lee et al., 1974; Pollard et al., 1979; Pope et al., 1983; Wijewardene and Waidyanatha, 1984; Crowder et al., 1985; Mueller et al., 1985). For example, yields from corn grown on the contour were about 12% greater than from corn grown with the slope (Smith, 1946; Sauer and Case, 1954). On land with a 7% slope, yields from cotton grown in rotation were increased 30%, while erosion was reduced nearly one-half (Hendrickson et al., 1963). In tests using rotations, the yields of corn were about 10% larger than continuous grown corn and weed control was improved (Ewing, 1978; Muhtar et al., 1982; Sundquist et al., 1982; Oldham and Odell, 1983/84; Barker et al., 1984).

The impact of soil degradation is clearly complex and a wide array of ecological factors in the soil interact to reduce crop production. Energy flow investigations along with soil and crop ecological investigations should help assess and measure the costs of environmental degradation and the benefits of sound environmental management.

Energy as a Measure of Chemical Pollution

Many insect and mite populations remain as minor or unimportant pests in crops because their natural enemies control them (DeBach, 1964; Huffaker, 1980). When insecticides and other pesticides are employed against one pest, its natural enemies or those of other pests may be reduced or eliminated. This has contributed to outbreaks of pests that were previously not a problem (Pimentel, 1971; Van den Bosch and Messenger, 1973; Adkisson, 1977). To correct for this chemical pollution problem, often more pesticide and/or other controls have to be applied and these corrective actions can be measured in terms of energy.

In the first quarter of this century, for example, the major pests of cotton in the southern United States were the boll weevil and cotton leaf worm (Newsom, 1962). When in 1945, we started using DDT, parathion, and other insecticides on cotton, several other insects and mites became more serious pests than they were previously. For instance, treatments for the boll weevil resulted in outbreaks of the cotton bollworm and cotton budworm (Ridgway et al., 1967; Cate et al., 1972; Lingren et al., 1972; Van Steenwyk et al., 1975; Johnson et al., 1976; Kinzer et al., 1977; Plapp and Vinson, 1977; Adkisson, 1977; Pimentel et al., 1977). To control these outbreaks, frequently, an additional five pesticide sprays had to be made (Pimentel et al., 1977). Assuming that each of these treatments required 1 kg of insecticide applied per hectare and about 100,000 kcal are required per kilogram of pesticide, then about 500,000 kcal are necessary to offset the chemical pollution for treating the boll weevil in cotton (Pimentel et al., 1977; Pimentel, 1980). If the offsite effects of the use of pesticides were also included, then the energy costs of offsetting these chemical pollution problems would be much greater (Pimentel et al., 1980; Pimentel and Levitan, 1986).

Other examples of how chemical pollution can be measured in energy terms are possible in agriculture, but this example should suffice. This approach has, of course, applications to chemical and other pollution problems in society.

IV. Conclusion

Most of the research in U.S. agriculture is conducted by individual scientists in an ad hoc manner that in some cases leads to problems in other sectors of food production and the environment. These problems could be avoided or reduced if investigators considered the implications of their research relative to the food system as a whole that includes the environment and socioeconomics. Certainly, a major accomplishment in agriculture will be when various scientific disciplines in agriculture start working together in multidisciplinary teams and the investigators adopt a holistic perspective of their investigations as it relates to the total agricultural, environmental, and societal system.

Recognizing the need for a holistic perspective in agriculture and the human food chain as it relates to the environment, a unified approach was proposed based on energy accounting. This technique is applicable to natural ecological food systems as well as the human food system. Using energy accounting in agriculture and the human chain and environment, it was possible to demonstrate that:

1. Both agriculture and natural ecological food systems depend primarily on solar energy. Agriculture is 80 to 95% dependent on solar whereas natural systems are 100% dependent on solar energy.
2. The productivity of agriculture and natural systems depends upon a quality environment.
3. The more intensely land, water, and biological resources are managed to produce food, the more fossil energy and human labor are required for crop and/or livestock production.
4. When biological diversity in agriculture is increased, using two plant species instead of a monoculture of one species, more solar energy can be fixed and more food can be produced per unit of land area than in the monoculture system.
5. Environmental resource degradation due to soil erosion and water runoff can be measured in energy terms.
6. The impact of chemical pollution on agriculture and environment can be measured by energy accounting.
7. Economic and social benefits in the food chain can be assessed in part by energy accounting. This accounting can assist in finding ways of improving and reducing the costs of agricultural production while supplying society most economically with its basic nutrient needs.
8. Energy accounting can be helpful in identifying areas of research that might lead to the development of technologies that will reduce energy inputs and make agriculture more profitable and more environmentally sustainable.

Table 1. Annual plant biomass production and light energy fixed by plants in the United States (Pimentel et al., 1978a).

Terrestrial	Millions of hectares	Biomass (dry) tonnes/ha	Total Biomass (dry) Mt
Farmland:			
Cropland	135	6	810
Cropland, idle	21	4	84
Cropland in pasture	36	4	144
Grassland in pasture	183	3	549
Forest & woodland	45	4	180
Farmsteads, roads	11	0.1	1
Other:			
Grazing land	117	2	234
Forest land	202	4	808
Other land (urban, marshes, desert, etc.)	167	0.1	17
Total	917		2,827
Aquatic			
Lakes and rivers	132	3	396
Grand Total	1,049		3,223

Total energy = 13.5×10^{15} kcal

Table 2. Energy inputs in corn (maize) production in Mexico using only manpower (Pimentel and Pimentel, 1979).

	Quantity/ha		kcal/ha
Inputs			
Labour	1,144	h	589,160
Axe and hoe	16,570	kcal	16,570
Seeds	10.4	kg	36,608
Total			642,338
Outputs			
Corn yield	1,944	kg	6,901,200
kcal output/kcal input			10.74
Protein yield	175	kg	

Table 3. Energy inputs in corn (maize) production in Mexico using oxen (Pimentel and Pimentel, 1979).

	Quantity/ha		kcal/ha
Inputs			
Labour	383	h	197,245
Ox	198	h	495,000
Machinery	41,400	kcal	41,400
Seeds	10.4	kg	36,608
Total			770,253
Outputs			
Corn yield	941	kg	3,340,550
kcal output/kcal input			4.34
Protein yield	85	kg	

Table 4. Energy inputs per hectare for 1983 conventional U.S. corn production (Pimentel et al., 1987b).

	Qty	10^3 kcal	Econ.
Labor (hrs)	10	7	50
Machinery (kg)	55	1,485	91
Fuel (liters)	115	1,255	38
N (kg)	152	3,192	81
P (kg)	75	473	53
K (kg)	96	240	26
Lime Stone (kg)	426	134	64
Corn Seeds (kg)	21	520	45
Cover crop seeds (kg)	---	---	---
Insecticides (kg)	1.5	150	15
Herbicides (kg)	2	200	20
Electricity (10^3 kcal)	100	100	8
Transport (kg)	322	89	32
Total		7,845	$523
Yield (kg)	6,500	26,000	
Output/input ratio		3.31	

Table 5. Inputs, corn yields, and fuelwood harvested per hectare by single species monoculture and two species system (Pimentel et al., 1987b).

	With Low Fertilizer		With Legume Tree	
	Qty.	10^3 kcal	Qty.	10^3 kcal
Labor (hrs)	400	210,000	500	262,500
Draft Animal (hrs)	200		200	
Concentrate (kg)	150	525,000	150	525,000
Stover and _Leucaena_ (kg)	295	885,000	295	885,000
Machinery (kg)	2.5	67,500	2.5	67,500
N (kg)	0	0	0	0
P (kg)	10	63,000	10	63,000
K (kg)	15	37,500	15	37,500
Ca (kg)	20	6,000	20	6,000
Seeds (kg)	15	60,000	15	60,000
TOTAL COSTS		1,838,000		1,906,500
Corn grain yield (kg)	1,000	4,000,000	1,500	6,000,000
Corn Stover yield (kg)	1,000	4,000,000	1,500	6,000,000
Residue harvested	0	0	0	0
Wood biomass yield dry (kg)	0	0	4,500	18,000,000
Fuel wood harvested	0	0	2,000	8,000,000
Biological nitrogen added (kg)	0	0	60	1,260,000

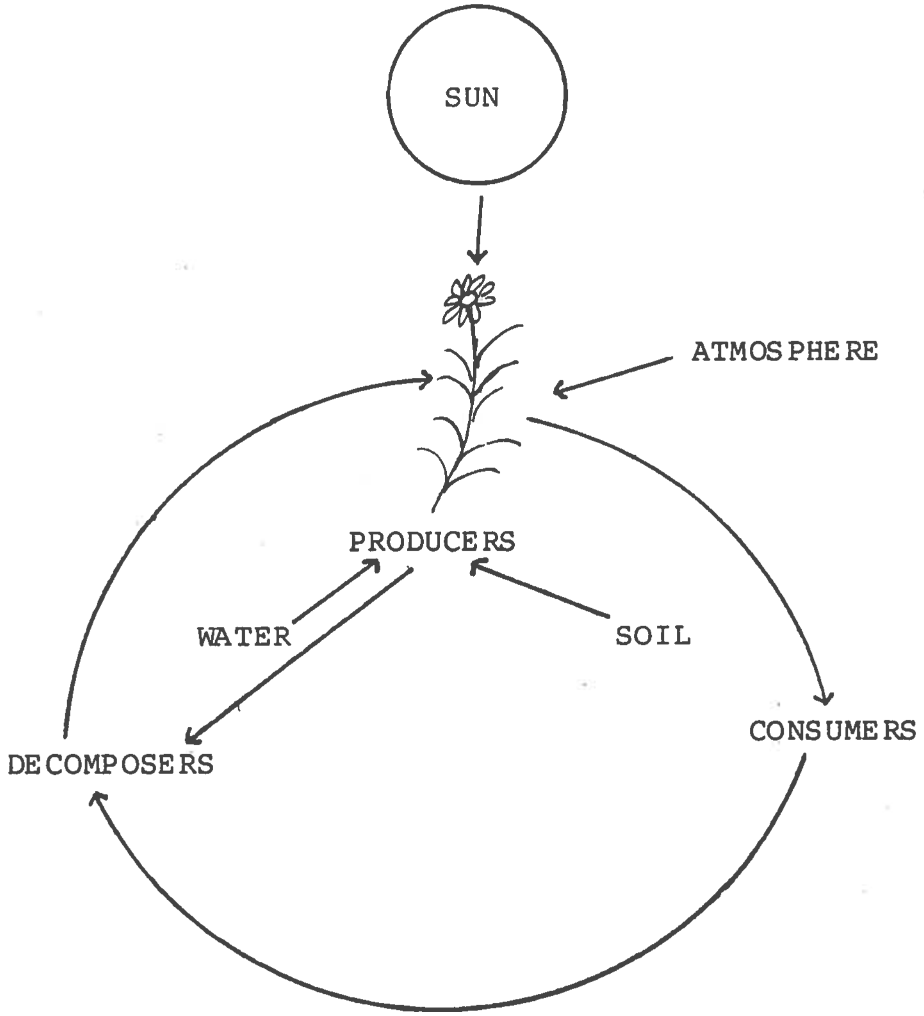
Table 6. Land resource requirements and structural materials and energy inputs for construction of energy facilities that produce 1 billion kWh/yr of electricity (assumed 30-year life for all facilities except for hydropower) (Pimentel et al., 1984).

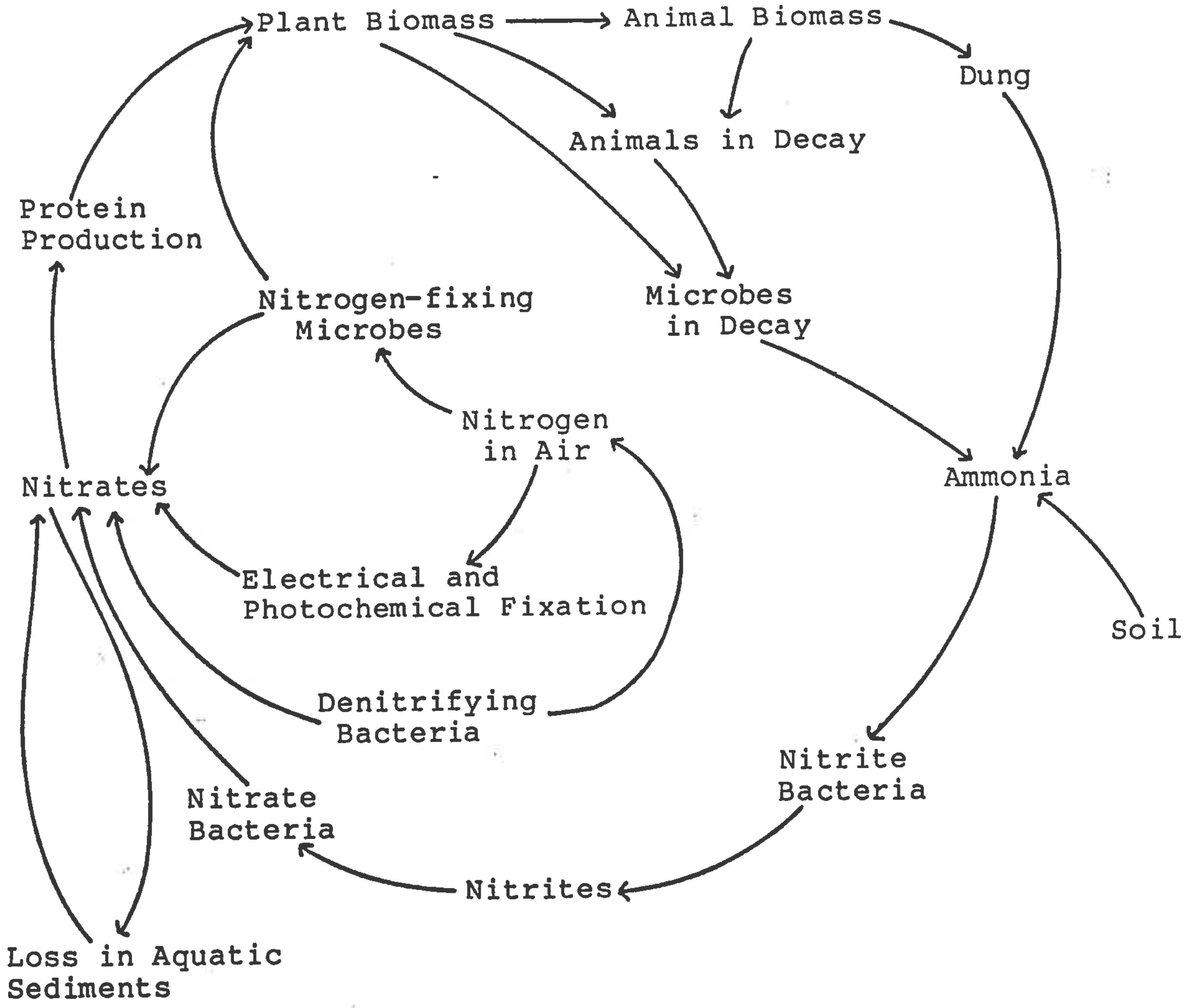
		Structural materials (tonnes x 10^3)				
Electrical Energy Technology	Land in hectares	Steel	Concrete	Other Materials	Energy Input kWh x 10^9	Energy Input/Output Ratio
Solar Thermal Central Receiver	800	59	255	32	1.6	1:19
Photovoltaics	600	---	---	---	1.8	1:17
Wind Power	2,700	48	114	3.3	1.1	1:29
Hydropower	13,000	12.3	674	---	0.7	1:86
Forest Biomass	330,000	0.3	0.2	---	0.006	1:500
Solar Ponds	9,000	*	*	*	*	*
Nuclear	68	0.2	1.2	---	0.03	1:0.34
Coal	90	0.3	0.2	---	0.006	1:0.32

* not available

Figure 1. A self-sufficient ecosystem consists of a network of energy and mineral flows with the major functional parts being producers, consumers, and decomposers.

Figure 2. The nitrogen biogeochemical cycle.


SUN
ATMOSPHERE
PRODUCERS
WATER
SOIL
CONSUMERS
DECOMPOSERS


Plant Biomass
Animal Biomass
Dung
Animals in Decay
Protein Production
Nitrogen-fixing Microbes
Microbes in Decay
Nitrogen in Air
Nitrates
Ammonia
Electrical and Photochemical Fixation
Soil
Denitrifying Bacteria
Nitrite Bacteria
Nitrate Bacteria
Nitrites
Loss in Aquatic Sediments

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