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ENERGY FLOWS IN AGRICULTURAL AND NATURAL ECOSYSTEMS

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ABSTRACT

In this analysis energy inputs to crop production, emphasizing corn or maize, is compared for a series of agricultural systems of increasing complexity. Solar energy captured in corn yield is 2 to 8 times higher under intensive modern management systems than in hand or animal powered systems. The ratio of energy output to energy input is 2.14 to 1 for a modern tractor system and decreases to 0.73 to 1 when hoe agriculture is practiced. The reason for the change in the ratio is mainly due to a decrease in labor energy costs in modern systems, although fossil fuel costs do increase.

Organic systems may or may not be more efficient than modern nonorganic systems depending upon the crops resistance to pests. Quality of the resources is also of great importance. Soil erosion and water are major problems which act to reduce yield and increase energy costs.

RESUMEN

En este análisis, los inputs de energía en la producción de cultivos, destacando el maíz, se comparan a una serie de sistemas agrícolas de complejidad creciente. La energía solar captada en la producción de maíz es de 2 a 8 veces superior en sistemas modernos de manejo intensivo que en sistemas manuales o de tracción animal. La relación entre output e input de energía es de 2,14 a 1 para sistemas modernos de tractores, y disminuye de 0,73 a 1 cuando se practica agricultura de azada. La razón del cambio en la relación se debe, principalmente, a la disminución en los costos en energía de la mano de obra en los sistemas modernos, aunque los costos en combustible fósil continúen incrementándose.

Los sistemas orgánicos pueden resultar, o no, más eficaces que los sistemas modernos no-orgánicos, dependiendo de la resistencia de los cultivos a las plagas. La calidad de los recursos posee también gran importancia. La erosión del suelo y el agua son también problemas principales que actúan reduciendo la producción e incrementando los costes de energía.

INTRODUCTION

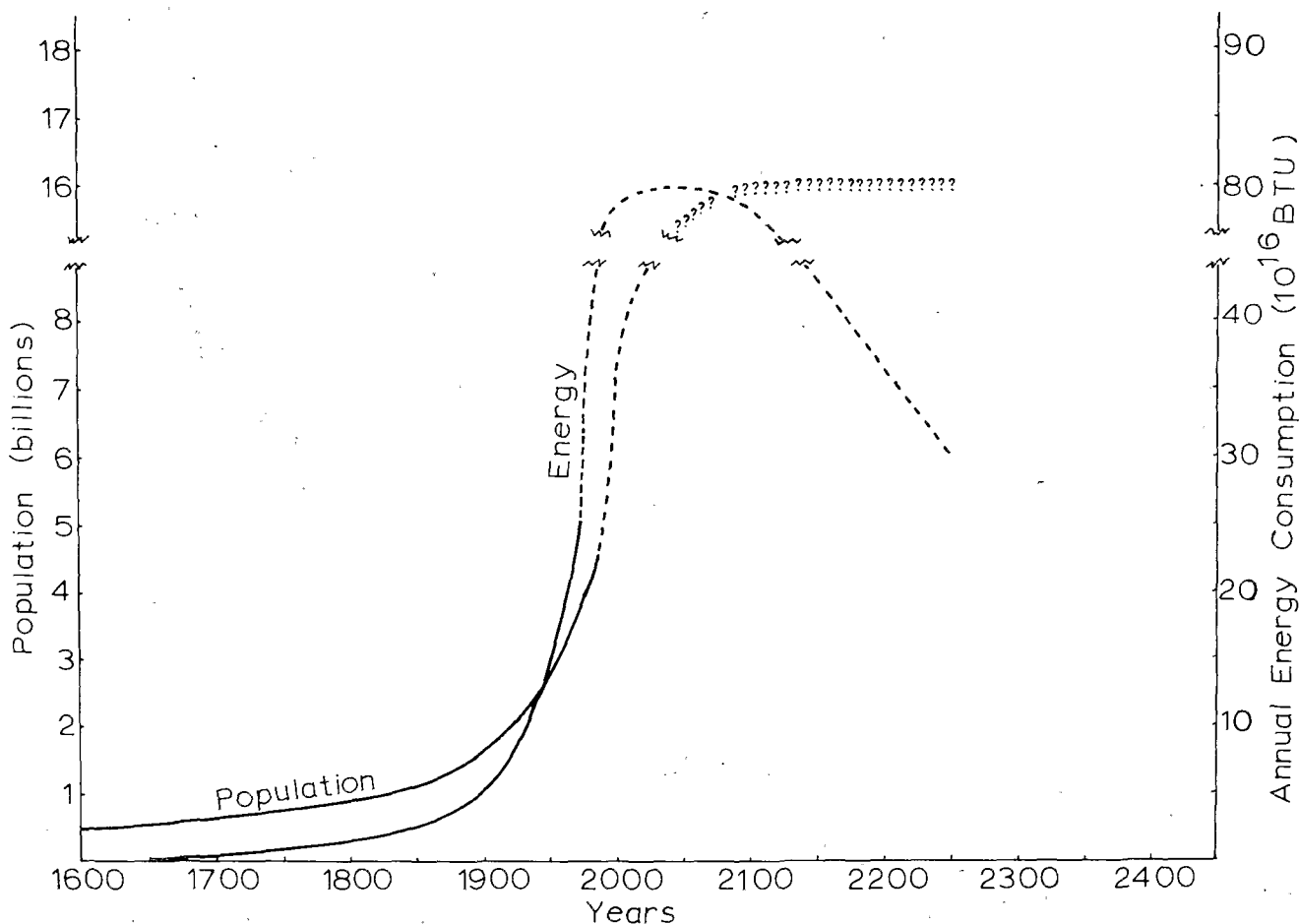
Natural and agricultural ecosystems of which humans are a part is fundamentally a network of energy and mineral flows. Green plants capture solar energy and convert it into chemical energy for use by the biological system using the elements of C, H, O, N, P, K, Ca, Mg, and others. Basic to the survival of humans and other animals are adequate suppliers of food that are supplied by the ecosystem.

For nearly a million years humans obtained their food like other animals, that is as hunter-gatherers. During this period humans were completely dependent on solar energy. It has been only during the last 10,000 years that humans harnessed draft-animals, water, wind, and fossil fuel power to augment human energy. Fossil energy has been used in agriculture for only 300 years.

One of the major forces moving humans from early slash-burn agriculture to more intensive type agricultural systems has been the growth in the world population (Figure 1). The world population is now at 4.7 billion (PRB, 1983) and is projected to grow to 6.2 billion by the turn of the century (FAO, 1981). Serious food shortages already exist in the world. About a half billion humans are now malnourished and the problem is rapidly growing in severity (FAO, 1981). It is projected that grain cereal deficits in developing nations will triple during the next 2 decades (FAO, 1981).

Producing food to conquer food shortages requires more than land, water, energy, and biological resources. The human food system also depends on the social, political, and economic structure of society. For example, surplus food is being produced in the United States and farmers are being paid \$35 billion not to produce

Figure 1. Estimated world population numbers (----) from 1600 to 1975 and projected numbers (-----) (????) to the year 2250. Estimated fossil fuel consumption (----) from 1650 to 1975 and projected (-----) to the year 2250 (Environmental Fund, 1979; Linden, 1980).



food while a half billion humans are malnourished in other parts of the world. The people who are hungry desire the food and the U. S. farmers desire to produce and supply the food. One major factor preventing these desires being met is economics. U. S. farmers cannot produce the food without economic support and the poor, hungry people of the world have no money to purchase the food. No matter how food is raised, paid for, and distributed, food production should double during the next 2 decades if malnourishment is to be dealt with, plus meet food needs for nearly 2 billion more humans added to the population over this period. Doubling food supplies will require making more efficient use of energy, land, water, and other ecosystem resources used in agricultural production. In this paper I plan to investigate how much solar energy can be harvested in crop biomass by intensive agricultural management and how this production is influenced by the quality of land, water, and biological resources in agroecosystems.

ENERGY INPUTS IN AGRICULTURAL PRODUCTION SYSTEMS

The foundation of the total life system rests on the unique capacity of plants to convert solar energy into stored chemical energy. This captured energy is then utilized by consumers in the ecosystem including humans. The success of agricultural production is measured by the amount of biomass energy captured in the crop as a result of manipulating plants, land, and water, while using human and animal power and fossil energy power.

The solar energy reaching a hectare during the year in temperate North America averages about 14×10^9 kcal (Reifsnyder and Lull, 1965). During a 4 month summer growing season in the temperate region nearly 7×10^9 kcal reach an agricultural hectare. Under favorable conditions of moisture and soil nutrients, corn is considered one of the most productive food and feed crops per unit area of land (Pimentel, 1980). For example, high yielding corn grown on the good soils of Iowa can produce about 7,000 kg/ha of corn grain plus another 7,000 kg/ha of biomass as stover. Converted to heat energy this totals 63×10^6 kcal (heat energy = 4,500 kcal/kg) and represents about 0.5 % of the solar energy reaching the hectare during the year (1 % during the growing season).

For other crops the efficiency conversion is much less than for corn. For example, potatoes with a yield of 40,000 kg/ha, have a dry weight of

about 8,000 kg/ha. Based on total biomass produced of 12,000 kg/ha and an energy value of 54×10^6 kcal., potatoes have a 0.4 % efficiency of conversion. Or a wheat crop, yielding 2,700 kg/ha of grain, produces a total of 6,750 kg biomass/ha, which has a heat energy value of 30×10^6 kcal. The conversion efficiency of sunlight into biomass in this system is only 0.2 %. All of these systems are relatively efficient, however, agricultural ecosystems as whole including pastures and rangeland are less efficient and the average rate of conversion is about 0.1 %. The average of 0.1 % conversion efficiency for agricultural is similar to that of U. S. natural vegetation (Pimentel *et al.*, 1978).

Although all these efficiencies for conversion are low relative to the total amount of solar energy reaching a hectare of land, they are still 2 to 5 times greater than the average conversion efficiency of U.S. natural vegetation, which is estimated to be about 0.1 % (Pimentel *et al.*, 1978).

In the above analyses only the energy in the biomass was assessed relative to the solar energy reaching the hectare. Agricultural crop production, however, requires additional energy inputs for tillage, seeds, weeding, and harvesting. In the following analysis, several different farming systems are examined along with their relative efficiencies in producing food energy.

Corn produced by hand in Mexico employing swidden or cut / burn agricultural technology requires only a man with an axe, a hoe, and some corn seed (Table 1). A total of 1,144 hours of labor is required to produce 1944 kg./ha. This 1,144 hours represents about 57 % of the total labor output for an adult per year. To calculate the energy input from labor in this case, I am assuming the individual is from the rural area of a developing country. Thus, this man is assumed to consume about 3,000 kcal of food per day and requires about 6,000 kcal of fuelwood for cooking (Pimentel and Pimentel, 1979). Little or no heat is needed because the region is assumed to be tropical. The family is assumed to consist of 4 individuals who each require about 9,000 kcal./day. To account for inputs for limited schools, public health, roads, police, and military, the equivalent of additional 9,000 kcal energy was added to the total per day. Thus, the labor input for a hectare of corn was calculated to be 9.4 million kcal. (Note, this is more than 15-times higher than just calculating the input for the food consumed by the individual laborer, which is only about 600,000 kcal (Pimentel and Pimentel, 1979).

Table 1. Energy in corn (maize) production in Mexico using only manpower.

INPUT

Item	Quantity/ha	kcal/ha
Labor	1,114 h ^a	9,362,000 ^c
Axe and hoe	16,570 kcal ^b	16,570 ^d
Seeds	10.4 kg ^b	36,608 ^d
Total		9,413,178

OUTPUT

Total yield	1,944 kg ^a	6,901,200 ^a
Kcal. output/kcal input		0.73

(a) Lewis, 1951.

(b) Estimated.

(c) See text for assumptions for calculating kcal input.

(d) Pimentel and Pimentel, 1979.

When the energy for making the axe and hoe and producing the seed is added to the human power input, the total energy input needed to produce corn by hand is about 9.4 million kcal/ha (Table 1). With a corn yield per hectare of 1,944 kg or 6.9 million kcal, the output/input ratio is only 0.73 (Table 1). It should be noted that nearly two thirds of the 9.4 million kcal input was biomass energy such as fuelwood. In one sense, therefore, fuelwood from outside of the crop hectare was being converted into food by supplying some of the human energy needs. Thus, although only 0.73 kcal was produced per input kcal, the system is profitable to human society because the 0.73 kcal produced was food.

If some of the 1,144 hours of manpower in the hand-powered corn system were replaced with 200 hours of ox-power, then human labor input might be reduced to 380 hours (Table 2). Hence, in this system labor input totalled 3.1 million kcal and is still the largest input. The feed for the ox for about 200 hours with a total work-capacity of 1,600 hr/yr was 150 kg of concentrate and 295 kg of hay (Morrison, 1956).

The total energy for the ox-system is calculated to be 4.6 million kcal, for an output/input ratio of 0.72 : 1 (Table 2). This ratio is similar to

hand-produced corn (Tables 1 and 2), but note the corn yield for the ox system was only 941 kg/ha compared with 1,944 kg/ha in the hand-powered system (Table 2). One reason for this low yield is that the corn had been planted on bottomland that had been cropped continuously for several years. In all probability the fertility of the soil on this bottomland was lower than that in the freshly planted slash/burn areas. If the nutrients were increased by either using fertilizers or dung, then the yields would be similar to the yield of hand-produced slash/burn corn (Table 1). Of course the energy input into the ox-powered system would have to be increased somewhat for the fertilizer nutrients.

Energy flow in corn production was examined for a horse-powered system that included all the other inputs for modern U.S. corn production (Table 3). A total of 120 hours of horse power were used to replace about 10 hours of the tractor power. Feed for a 682 kg (1,500 lb) horse was calculated to be 136 kg of corn and 136 kg of hay (Table 3) (Morrison, 1956). This system assumes that a horse works 1,600 hours per year, thus only 7.5 % or 120 hours of the total yearly feed is allocated for the hectare of corn produced.

Table 2. Energy inputs in corn (maize) production in Mexico using oxen.

INPUT		
Item	Quantity/ha	kcal/ha
Labor	383 h ^a	3,120,750 ^c
Ox	198 h ^a	
Concentrate	150 kg.	525,000 ^c
Hay	295 kg	885,000 ^c
Machinery	41,400 kcal ^b	41,400 ^d
Seeds	10.4 kg ^b	36,608 ^d
Total		4,608,758

OUTPUT		
Corn yield	941 kg ^a	3,340,550
Kcal output/kcal input		0.72

- (a) Lewis (1951).
 (b) Estimated.
 (c) See text for assumptions used in calculating these inputs.
 (d) Pimentel and Pimentel (1979).

The horse-powered system required 120 hours of human labor. For this system we assume that an average U.S. laborer utilizes an average of 76 million kcal of energy per year (DOE, 1983). This energy includes all food, housing, school, roads, police, military, etc. For a family of 4 this totals 304 million kcal. If the farm laborer works 120 hours, this represents 6 % of his total output or 18.2 million kcal input for the one hectare of corn (Table 3). The total energy input in the horse-system was therefore 26.7 million kcal. Thus, the output / input ratio was 0.92 : 1 (Table 3). This ratio is certainly better than either the hand-powered or the ox-powered systems (Tables 1-3).

The energy flow in tractor-powered agriculture is distinctly different from that of man-, ox-, and horse-powered agricultural systems (Tables 1-4). Typically U.S. corn production relies heavily on machinery for power. The total manpower input is dramatically reduced to only 10 hours compared with 1,144 hours for the hand-powered

system in Mexico or about 1 / 120th that of the hand-powered system (Tables 1 and 4). The input for labor in the U.S. system is only 1.9 million kcal of energy for the growing season, which is similar to the inputs for nitrogen fertilizer and irrigation.

Balanced against this low manpower input is the significant increase in fossil energy input needed to run the machines that replace human labor. In 1983 the energy inputs (mostly fossil fuel) required to produce a hectare of corn averaged about 11.5 million kcal/ha or the equivalent of about 1,150 liters of oil (Table 4). Then based on a corn yield of about 7,000 kg/ha, or the equivalent of 24.5 million kcal energy, the output / input ratio is 2.14 : 1. Note, the fossil energy input in this system represents about 18 % of the solar energy captured by the above ground total corn biomass (63×10^6 kcal).

How do solar energy inputs relate to corn biomass energy harvested? During the year, as men-

Table 3. Energy inputs per hectare for corn production in the United States employing horse power.

INPUTS		
Item	Quantity/ha	kcal/ha
Labor	120 hr	18,200,000
Machinery	15 kg	27,000
Horse	120 hr	
Corn	190 kg	665,000
Hay	190 kg	570,000
Irrigation	2.25×10^6 kcal	2,250,000
Electricity	35 kwh	100,000
Nitrogen	152 kg	2,128,000
Phosphorus	75 kg	225,000
Potassium	96	134,000
Lime	426 kg	134,400
Seeds	21 kg	520,000
Insecticides	3 kg	300,000
Herbicides	8 kg	800,000
Drying	3,300	660,000
Transportation	300 kg	80,000
Total		26,733,000

OUTPUT

Total yield	7,000	24,500,000
Kcal output/kcal input		0.92

tioned, 14 billion kcal of solar energy reaches an agricultural hectare. With an above ground corn biomass of 14 t / ha, the amount of sunlight captured is 0.45 % (0.22 % for corn grain itself based on food energy) (Table 4). For the hand-powered system the percentage solar energy captured as corn was only 0.13 % (Table 1) and for the ox-powered the percentage was only 0.06 % (Table 2). Thus, the U.S. intensive management system was 2 —and 8— times more productive, respectively, in converting solar energy into corn grain than the hand-powered and ox-powered systems.

Corn yield is now at about 7,000 kg / ha in the United States. How high can these yields go? In general, it appears that corn yields have tended to reach a plateau since 1970 (Figure 2). Note, the fluctuations in yields are rising in amplitude. This is expected when the production system is

stressed for near maximum production. The result of this stress is that any limiting factor affecting the system is more apt to cause a major decline.

This emphasizes the importance of an integrated production system to achieve maximum corn yields. The corn variety must be a suitable genotype that will grow best under high fertilizer levels, with sound pest control, ample moisture, suitable temperature levels, and a long growing season.

With a suitable corn hybrid and ideal growing conditions, corn yields may reach 20 t / ha of grain (about 300 bu / acre). For a total biomass of 40 t / ha, this represents 180 million kcal of energy or conversion of about 1.3 % of solar energy into corn biomass. This is about 10-times greater than the conversion of solar energy by the hand-powered system.

The limitation of the approach of increasing one

input while holding all others constant is well illustrated with nitrogen (Figure 3). Note that in Iowa when no nitrogen was applied, the yield was about 2,200 kg/ha. Corn yields continued to increase to 6,900 kg/ha as nitrogen applications rose to about 230 kg/ha. With further applications of nitrogen, corn yields actually declined. Too much nitrogen fertilizer is toxic to corn.

The toxic condition with nitrogen applied at 270 kg/ha or greater might be offset by increasing the applications of P and K while at the same time increasing the amount of water available to the crop. Also desirable would be having a corn hybrid that is tolerant of high fertilizer levels.

ORGANIC AGRICULTURAL SYSTEMS

Organic agricultural systems have a major objective to maintain soil productivity and thus keep agriculture sustainable (Pimentel *et al.*, 1983). Organic farming is usually defined as production systems that avoid the use of synthetic chemical fertilizers, pesticides, and growth regulators (USDA, 1980). The essential nutrients of N, P, and K are provided by organic wastes including leaves, dung, and legumes grown as a nitrogen source (e. g., sweet clover), and soil amendments like glauconite for K, and rock phosphate for P.

If cattle manure contains 5.6 kg of N, 1.5 kg of

Table 4. Energy inputs per hectare for corn production in the United States (Pimentel and Wen Dazhong, 1984).

INPUT		
Item	Quantity/ha	kcal/ha
Labor	10 hr	1,900,000
Machinery	55 kg	990,000
Gasoline	40 l	400,000
Diesel	75 l	855,000
Irrigation	2.25×10^6 kcal	2,250,000
Electricity	35 kwh	100,000
Nitrogen	152 kg	2,128,000
Phosphorus	75 kg	225,000
Potassium	96 kg	134,000
Lime	426 kg	134,400
Seeds	21 kg	520,000
Insecticides	3 kg	300,000
Herbicides	8 kg	800,000
Drying	3,300 kg	660,000
Transportation	300 kg	80,000
Total		11,472,000

OUTPUT		
Total yield	7,000 kg	24,500,000
Kcal output/kcal input		2.14

Figure 2. U. S. corn yields from 1909 to present.

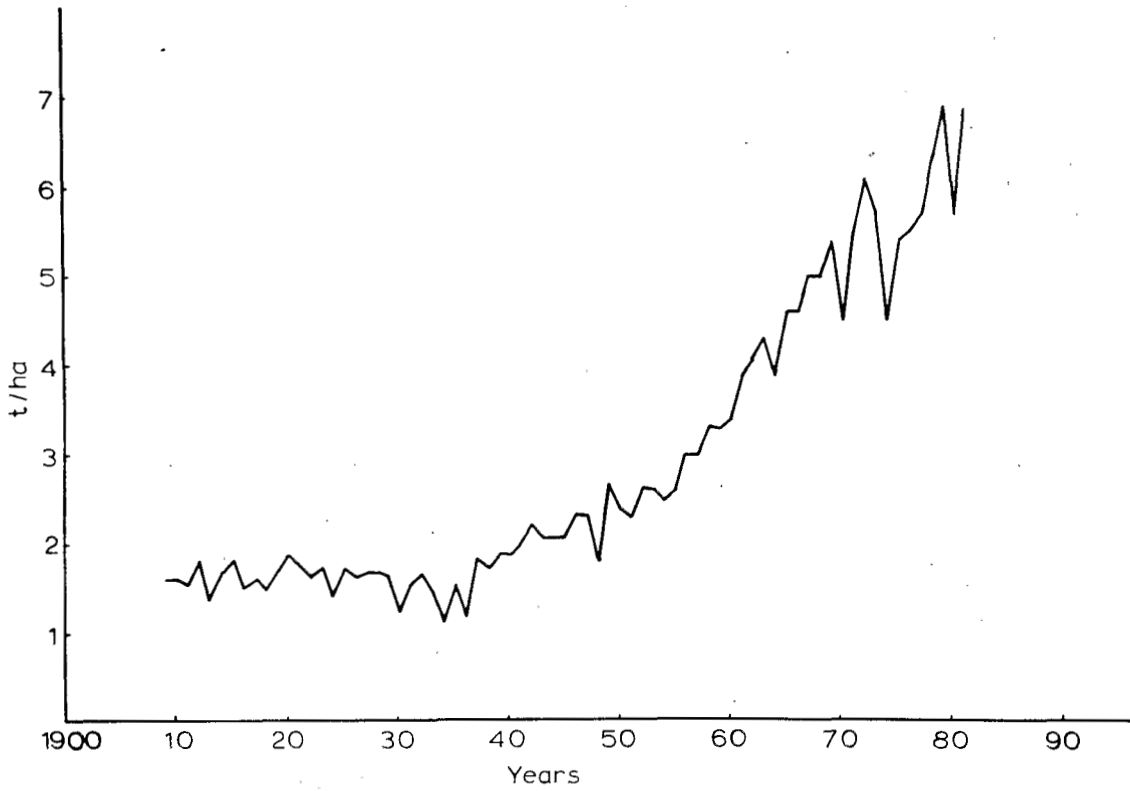
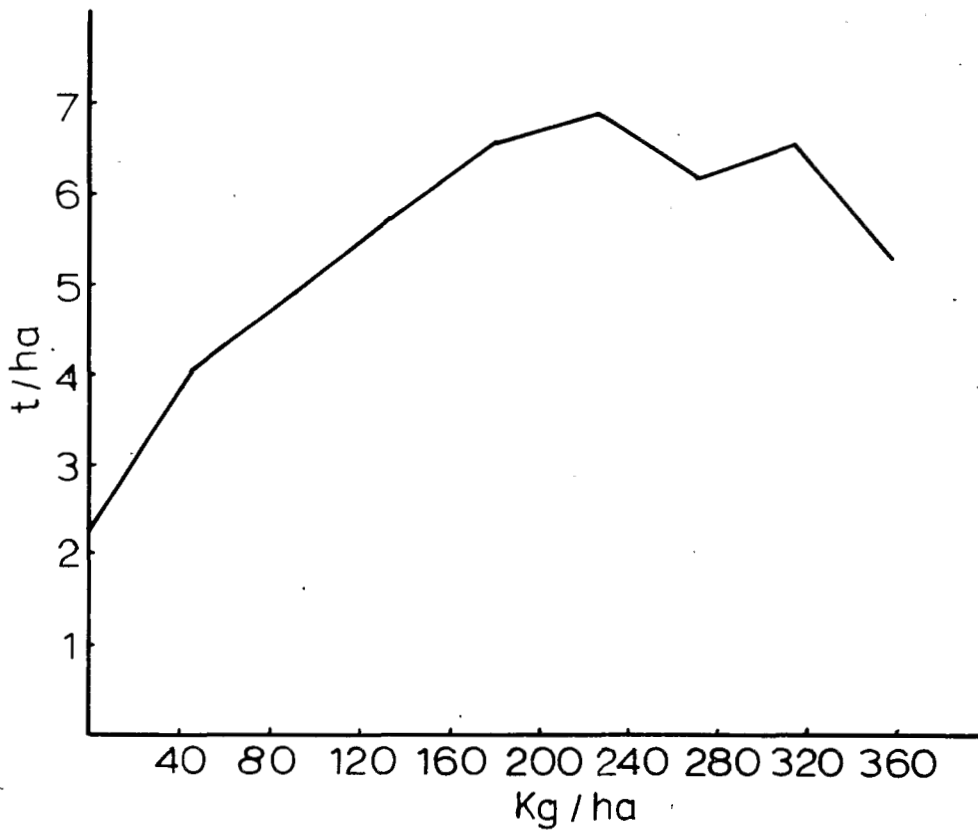


Figure 3. Corn yields (kg / ha) with varying amounts of nitrogen with the phosphorus application held constant at 38 kg / ha (Munson and Doll, 1959).



P, and 3 kg of K per wet ton, then to meet nitrogen needs (152 kg / ha) for corn about 27 tons of manure would have to be applied per hectare per year. If sweet clover or a similar legume has to be utilized to return N to the soil, then in essence 2 hectares of land are required to raise one hectare of corn. One hectare of the land is in fallow with sweet clover fixing nitrogen each year. Corn is then planted on this land the following year. A hectare of sweet clover will fix about 168 kg of N per season (Pimentel *et al.*, 1983).

Using livestock manure as the prime source of nutrients for corn production resulted in an energy output / input ratio of about 7 : 1 compared with about 4 : 1 for the conventional systems (Pimentel *et al.*, 1983). The labor input, however, for the organic farming system was 54 % greater than the conventional. Collecting and applying livestock manure or other organic matter requires significant inputs of labor. An analysis of wheat production by organic and conventional farming systems provided results that were quite similar to those of corn (Pimentel *et al.*, 1983).

Organic potato and apple production, however, were both significantly less energy efficient than conventional potato and apple production (Pimentel *et al.*, 1983). The reason for this inefficiency is that without pesticides potato yields were reduced by 50 % and apple yields reduced by 95 % (Pimentel *et al.*, 1983). Reducing yields by 50 to 95 % of the crops when no pesticides were used, while including all the normal cultural inputs made organic potato and apple production much less efficient than conventional production. Corn and wheat on the other hand can be grown without insecticides, fungicides, and herbicides, since pest losses increased only 1 to 2 % when no pesticides were applied (Pimentel *et al.*, 1983).

Thus, organic farming systems for some crops can be nearly twice as energy efficient as conventional agricultural systems whereas for other highly pest susceptible crops organic agriculture may be highly inefficient. Labor inputs for organic systems are generally 20 to 60 % greater than conventional systems (Pimentel *et al.*, 1983).

QUALITY OF LAND, WATER, AND BIOLOGICAL RESOURCES

Land is an essential resource for food production. Most or 97 % of all food that humans consume in the world comes from the land, only about 3 % comes from fish and related organisms that live in the world's aquatic habitats

(Pimentel *et al.*, 1975; CEQ, 1980). To produce this food, agriculture utilizes about 34 % of the total world land area for crop and livestock production.

Sound land use practices are needed everywhere in the world. Valuable agricultural lands are being degraded by various means but especially by soil erosion (Pimentel *et al.*, 1976; CEP, 1980; Eckholm, 1982). Erosion diminishes the productivity of agricultural land, and is a serious threat to sustainable U.S. and world agriculture (Pimentel *et al.*, 1976; GAO, 1977; SCS, 1977; OTA, 1982). Average soil loss from U.S. croplands is estimated to range from 11 to 20 t / ha per year and from harvested forestlands erosion ranges from 0.5 to 2 t / ha (GAO, 1977; SCS, 1977; USDA, 1980; 1981). Soil however, is formed extremely slowly; under agricultural conditions the rate is 0.5 to 2 t / ha per year (Swanson and Harshbarger, 1964; Larson, 1981).

In many developing nations soil erosion is estimated to be twice as bad as it is in the United States (Ingraham, 1975). In India, for example, it is reported that an average of 67 t / ha of soil are being lost from the land annually (Ahmad, 1973).

Soil loss adversely affects crop productivity by (i) reducing organic matter and fine clays, thus resulting in a loss of plant nutrient holding capacity; (ii) reducing water holding capacity; and (iii) restricting rooting depth as the soil thins (OTA, 1982). In some regions of the southern United States, soil losses during the past 100 to 200 years have resulted in yield reductions that range from 25 to 50 % for crops such as corn, soybeans, cotton, oats, and wheat (Adams, 1949; Buntley and Bell, 1976; Langdale *et al.*, 1979). Nonetheless, crop yields in most U.S. regions have been rising despite the impacts of soil erosion because of increased energy inputs (e. g., fertilizers and pesticides) and the use of such advanced technologies as high yielding crop varieties (Pimentel *et al.*, 1976; OTA, 1982).

With about 10 tons of soil lost per hectare per year, the quantity of soil nutrients being lost with the soil are 50 kg of N, 5 kg of P, 100 kg of K, and others (Pimentel and Moran, 1983). The light weight organic matter is the first material to be removed with the eroded soil. Reducing the organic matter content of the soil will also reduce crop yields. For example, decreasing soil organic matter from 3.8 % to 1.8 % will decrease crop yields about 25 % (Lucas *et al.*, 1977).

It is difficult to make a general statement about the effects of soil erosion on crop production

because it depends on crop type, soil nutrients, soil structure, topsoil depth, drainage, temperature, and moisture. The evidence suggests that in the United States for each 2.5 cm. (1 inch) of soil lost, corn production is reduced about 5 % or about 350 kg if the yield were potentially 7,000 kg / ha (Pimentel *et al.*, 1976). To offset the reduction of this soil degradation using energy inputs such fertilizers would require about 350,000 kcal or nearly 350 liters of oil equivalents (Pimentel *et al.*, 1981).

Water is another essential resource for crop production and is the single most important factor in limiting crop production in the world (Pimentel *et al.*, 1982). Crops require tremendous amounts of water just to replace the water that is transpired. A corn crop that produces 5,600 kg of grain per hectare will take up and transpire about 2.4 million liters of water per hectare during the growing season (Penman, 1970). To irrigate a corn crop under arid conditions would require about 4 million liters of water per hectare. To pump this much water from an underground source only 30 m deep would require about 12 million kcal of fuel (Batty and Keller, 1980). In general, irrigated crop production requires 3 times more energy for production compared with rainfed corn when human labor inputs are not included in the calculation (Pimentel *et al.*, 1982).

Natural biota are also essential to a productive agroecosystem. Soil biota, including fungi, bacteria, insects, and earthworms, play a major role in degrading organic wastes and recycling the nutrients (N, P, K, and others) for re-use by crop plants (Pimentel *et al.*, 1980). In fact, these organisms are an integral part of the soil.

Other biota, such as pollinators, are essential for many agricultural crops (Levin, 1983). Without pollinators, some crops like fruits and some vegetables could not be produced. Substituting human labor for bee pollination would be exceptionally energy intensive and in fact an impossible task.

CONCLUSION

Increasing the energy inputs in agroecosystems

will increase the solar energy converted into crop biomass per unit kcal invested in manipulation. For example, the U.S. tractor-powered corn-production system with only 10 hours of manpower and an input of 11.5 million kcal was more efficient in producing food energy than either the hand-powered or draft-animal-powered systems that had lower energy inputs for agroecosystem manipulation. Increasing fertilizers or other inputs will not result in raising yields indefinitely because of the biological principle of diminishing returns with increasing quantities of fertilizers and other inputs per hectare.

Soil, water, and biological resource quality play an important role in determining agricultural productivity and output return per energy input. Using high quality land, water, and biological resources, a larger quantity of food can be produced with the same inputs of energy than using poor quality land, water, and biological resources. Agricultural systems can be made more productive than natural systems if the ecosystem is soundly managed and an appropriate array of crop plants are utilized. Although total biomass production measured in energy terms is important for some agricultural crops such as forages, in most cases society is seeking specific types of nutrients including carbohydrates, proteins, vitamins, fats and minerals. Thus, any assessment of energy efficiency in agricultural ecosystem production must take into account the particular nutrients that are sought and not just food and biomass energy value.

It now appears that U.S. crop yields are approaching a plateau where the rate of crop yield increases is declining. U.S. crop yields will probably continue to increase at least for the next 2 decades, but the rate of increase will be slower. With high yields and increased intensity of management, the amplitude of fluctuations in yields should grow.

Land degradation, especially soil erosion, is rapidly reducing land productivity in the world. Already, large amounts of fossil energy are being utilized to offset erosion and reduced soil productivity. A major effort is needed worldwide to protect the productivity of agricultural soils that are essential to food production.

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