12 Energy Inputs in Crop Production in Developing and Developed Countries*

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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	Yield (kg)	Energy Harvest 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.

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