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Article

Energy Inputs in Food Crop Production in Developing and Developed Nations

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Abstract: Detailed energy outputs and inputs were assessed for the following crops, cultured in the U.S. and developing countries: corn, wheat, rice, soy, potato, cassava, tomato, citrus and apple. In addition, the labor input for each crop was analyzed.

Keywords: Agriculture, crops, developed and developing countries, energy, food, renewable energy

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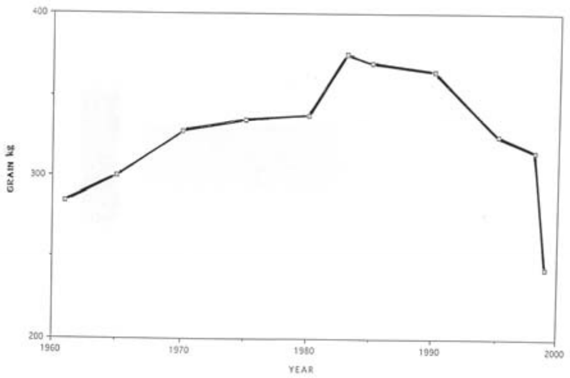
Introduction

More than 3.7 billion people are malnourished in the world today [1]. This is the largest number and percentage of malnourished humans ever recorded. The world human population is currently at more than 6.7 billion and nearly a quarter million people are added to the population daily [2]. Based on the current rate of increase, the world population is projected to double to approximately 13 billion in less than 60 years [2]. By 2050, a population of 9.5 billion is projected [2].

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, confirm the serious nature of the global food shortages [3]. For example, the *per capita* availability of world cereal grains has been declining for the past 24 years (Figure 1). Although grains make up about 80% of the world's food supply, approximately half of the world’s population cannot afford grains. For this reason, prices of grains have not increased greatly during the past decade. However, because of biofuel production, especially corn ethanol, food shortages and food prices have recently increased from 10% to 50% [4].

Figure 1. World per capita grain production from 1960 to 2000 [88].



As the world population continues to expand, greater pressure is being placed on resources essential for food production, including fossil energy. The human population grows exponentially, while food production increases arithmetically. The result is the current food deficit. The World Health Organization reports that nearly 60% of the world population is malnourished – the largest number in world history. Degradation and depletion of land, water, energy, and biological resources vital to agriculture, have continued unabated, further restricting agricultural production [5]. Recent increases in crop yields have occurred in fossil-fuel dependent agriculture in developed countries, but intensive agricultural techniques contribute in some cases to environmental degradation, such as soil erosion [5].

This article assesses the current use of energy in developed and developing countries in their food crop production systems, including some systems dependent on hand labor and draft animal power.

Energy Resources

People rely on various sources of energy and power. These sources range from human, animal, wind, tidal, and water energy to wood, coal, gas, oil, solar, and nuclear sources of fuel and power. Using fossil fuel resources enables a nation to feed an increasing number of humans, and improves the general quality of life in many ways, including protection from malnourishment and numerous other diseases [6].

About 473 quads (1 quad = 10^{15} BTU = 1.05 x 10^{18} Joules) from fossil and renewable energy sources are used worldwide per year [7]. The current high rate of energy expenditure is related directly to many factors, including rapid population growth, urbanization, and high resource-consumption rates. Increased energy use also contributes to environmental degradation [5]. Energy use has been growing at a rate even faster than the rate of growth of the world population. From 1970 to 1995, energy use has been doubling every 30 years whereas the world population has been doubling every 40- 0 years [2, 7]. In the near future, energy use is projected to double every 32 years while the population is projected to double in about 50 - 60 years [2, 7].

About 60% of all the solar energy captured by photosynthesis and incorporated in biomass production worldwide is used by humans (Pimentel, unpublished data). This amount of energy, though very large (approximately 720 quads), is inadequate to meet human needs. To compensate for the high demand, about 413 quads of fossil energy (oil, gas, and coal) are utilized each year worldwide [7]. Of this amount, 100.9 quads are utilized in the United States (about 19% in the food system) [8]. The U.S. population consumes about 68% more fossil energy than all the solar energy captured by harvested U.S. crops, forest products, and all other vegetation each year (Table 1).

Table 1. Total amount of above ground biomass except for some crops that include underground biomass and solar energy captured each year in the United States. An estimated 32 x 10^{15} BTU of sunlight reaching the U.S. per year suggests that the green plants in the U.S. are collecting 0.1% of the solar energy [44-47].

Crops	901 x 10^6 tons	14.4 x 10^{15} BTU
Pasture	600 x 10^6 tons	9.6 x 10^{15} BTU
Forest	527 x 10^6 tons	8.4 x 10^{15} BTU
Total	2,028 x 10^6 tons	32.4 x 10^{15} BTU

Industry, transportation, home heating, and food production account for most of the fossil energy consumed in the United States [8]. *Per capita* use of fossil energy in the United States is 9,500 liters of oil equivalents per year, more than 12-times the *per capita* use in China and some other developing countries (Table 2) [5]. In China, most fossil energy is used by industry, but a substantial amount, approximately 25%, is used for agricultural production, food distribution, and cooking [9].

Table 2. Resources used and/or available per capita per year in the U.S., China, and the world to supply basic human needs [8].

Resources	**U.S.**	**China**	**World**
Land (FAOSTAT, 2001)			
Cropland (ha)	0.48	0.08	0.22
Pasture (ha)	0.79	0.33	0.52
Forest (ha)	0.79	0.11	0.59
Total (ha)	2.78	0.46	1.97
Water (liters x 10^6)	2.0	0.46	0.60
Fossil fuel (BP, 2005 Oil equivalents (liters)	9,500	1,400	2,100

The less than two billion people who live in the world's developed nations consume 70% of the world's fossil energy annually, while the more than four billion people in developing nations use only 30% [7]. The United States, with 4.5% of the world's population, consumes about 22% of the world's fossil energy output (Table 3) [5]. Fossil energy use in the many U.S. economic sectors has increased 10 to 20-fold in the past three to four decades, attesting to America's heavy reliance on this finite energy resource to support an affluent lifestyle [5].

Developing nations that have high rates of population growth are increasingly using fossil fuel in agricultural production to meet increasing demand for food and fiber. In China between 1955 and 1992, there was a 100-fold increase in fossil energy use in agriculture for irrigation and for producing fertilizers and pesticides [9].

Table 3. Annual fossil and solar energy use in the U.S. and world (quads = 10^{15} BTU) [8].

Fuel	U.S.	World
Petroleum	40.1	168
Natural gas	23.0	103
Coal	22.3	115
Nuclear	8.2	28
Biomass	3.0	30
Hydroelectric power	3.4	27
Geothermal and wind power	0.4	0.8
Biofuels	0.5	0.9
Total	100.9	472.7

Yet, worldwide fertilizer production has declined more than 22% per capita during the last decade probably due to fossil fuel shortages, high prices, as well as economic transitions in Eastern Europe and developing countries [10]. The long term projections of the availability of fossil energy resources for fertilizers and for all other purposes are discouraging because of the limited quantities of fossil fuels.

The world supply of oil and natural gas is projected to last about 40 - 60 years [11-14]. Coal is projected to last 50 to 100 years [5, 11]. However, these estimates are based on current consumption rates and current population numbers. If all people in the world enjoyed a standard of living and consumed energy at a rate similar to that of the average American, and the world population continued to grow at a rate of 1.2%, the world's fossil fuel reserves would last only about 17 years.

If we continue to hope that new discoveries of oil will postpone when oil and natural gas disappear, this is wishful thinking. A recent report indicates that the world is consuming 27 billion barrels of oil annually. However, the rate of discovery has fallen to only seven billion barrels (W. Youngquist, Professional Geologist, Eugene, Oregon, personal communication 2000). Thus, humans are burning nearly four times as much oil as they find each year worldwide.

Youngquist [11] 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. Domestic oil and gas are imported in ever increasing amounts yearly [8], indicating that neither is now sufficient for domestic needs and supplies. Domestic oil and natural gas production will be substantially less in 15 years than it is today. Analyses suggest that as of 2008 the United States has consumed about 90% of the recoverable oil that was ever in the ground and that we are currently consuming the last 10% of our oil [8]. The United States is now importing more than 63% of its oil. This puts the U.S. economy at risk due to fluctuating oil prices, volatile political situations, such as the 1973 oil crisis and the current Iraq War.

By using available renewable energy technologies, such as biomass and wind power, an estimated 200 quads of renewable energy could be produced worldwide using 20% to 26% of the land area (Yao Xlang-Jun, personal communication, Cornell University, 1998) [15]. It should be noted that 200 quads is less than half of the energy currently consumed. Producing the 200 quads of renewable energy may require transferring some important pasture and forest land to energy production. A self-sustaining renewable energy system producing 200 quads of energy per year would be insufficient for the current population of 6.7 billion people in the world at the current fossil energy consumption rate [5]. A sustainable energy program might be possible for a sustainable population of only two billion people, but not the current 6.7 billion people in the world [15].

Food Crop Production, Energy Inputs and Economic Costs

A total of 12 crops were selected for this analysis of energy inputs and economic costs of food production systems in developed and developing countries. The selected crops, which include rice, corn, wheat, soybeans, cassava and potato, provide most of the world's food supply. Earlier we mentioned that cereal grains make up about 80% of the world's food and it should be mentioned that cassava, potato, and sweet potato play an important role in providing food for more than two billion people [16]. Apples, oranges, and tomatoes were included for examples of desirable crops that provide limited nutrients worldwide.

Corn

The Food and Agriculture Organization [17] and others [18] report that corn is one of the world's major cereal crops. Under favorable environmental conditions, corn is one of the most productive crops per unit area of land. 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.

Investing many hours of labor, a person can produce corn using little fossil energy (Table 4). Corn production by hand in Indonesia requires about 634 hours of labor and five hours of bullock power per hectare, an energy expenditure of 4.0 million kcal. With a corn yield of 1,200 kg/ha in Indonesia (6.9 million kcal), the energy input:output ratio is 1:1.08 (Table 4). 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 and little or no fossil energy is needed for the animals.

Table 4. Energy inputs of corn production per hectare in India and Indonesia.

Inputs	Quantity	kcal x 1000
Labor	634 hrs[a]	1,170[g]
Bullock (pair)	200 hrs[h]	1,300[b]
Machinery	10 kg[c]	185[d]
Nitrogen	71 kg[f]	1,200[e]
Phosphorus	36 kg[f]	145[e]
Manure	600 kg[a]	961[b]
Seeds	33.6 kg[f]	121[d]
TOTAL		5,082
Corn yield = 1,721 kg[a]	6,200[d]	
	Kcal input: output = 1:1.08	

a) Djauhari *et al*. (1988) [48]; b) Tripathi and Sah (2001) [34]; c) Estimated; d) Pimentel (1980) [22]; e) FAO (1999) [49]; g) R. S. Doughty (unpublished); h) Per capita use of fossil energy in Indonesia is about 369 liters of oil equivalents per year (BP, 2005) [33]; i) Jeer Organization (1990) [50]

The energetics of mechanized corn production are distinctly different from those of labor-intensive food-crop production. Corn production in the United States today is typical of intensive crop production technology. The total input of human power is only 11.4 hrs per hectare compared with 634 hrs in the labor-intensive system in India and Indonesia discussed previously (Tables 4 and 5). In the U.S. system, approximately 25% of the total energy is consumed in labor-reducing mechanization (Table 5).

Table 5. Energy inputs and costs of corn production per hectare in the United States.

Inputs	**Quantity**	**kcal x 1000**	**Costs $**
Labor	11.4 hrs[a]	462[b]	148.20[c]
Machinery	55 kg[d]	1,018[e]	103.21[f]
Diesel	40 L[i]	405[j]	20.80[g]
Nitrogen	155 kg[a]	2,480[k]	85.25[l]
Phosphorus	79 kg[a]	328[m]	48.98[n]
Potassium	84 kg[a]	274[o]	26.04[p]
Lime	1,120 kg[q]	315[r]	19.80
Seeds	21 kg[d]	520[d]	74.81[s]
Irrigation	8.1 cm[t]	320[u]	123.00[v]
Herbicides	6.2 kg[w]	620[z]	124.00
Insecticides	2.8 kg[x]	280[z]	56.00
Electricity	13.2 kWh[y]	34[aa]	0.92
Transport	204 kg[bb]	169[cc]	61.20
TOTAL		8,228	$926.97
Corn yield 9,400 kg/ha[dd]		33,840	Kcal input: output 1:4.11

a) NASS, 2003 [51]; b) It is assumed that a person works 2,000 hrs per year and utilizes an average of 8,000 liters of oil equivalents per year; c) It is assumed that labor is paid $13 an hour; d) Pimentel and Pimentel, 1996 [52]; e) Prorated per hectare and 10 year life of the machinery. Tractors weigh from 6 to 7 tons and harvesters 8 to 10 tons, plus plows, sprayers, and other equipment; f) Hoffman *et al*., 1994 [53]; g) Wilcke and Chaplin, 2000 [54]; h) Input 11, 400 kcal per liter; i) Estimated; j) Input 10,125 kcal per liter; k) Patzek, 2004 [55]; l) Cost $.55 per kg; m) Input 4,154 kcal per kg; n) Cost $.62 per kg; o) Input 3,260 kcal per kg; p) Cost $.31 per kg; q) Brees, 2004 [56]; r) Input 281 kcal per kg; s) USDA, 1997 [57]; t) USDA, 1997 [58]; u) Batty and Keller, 1980 [59]; v) Irrigation for 100 cm of water per hectare costs $1,000 (Larsen *et al*., 2002) [60]; w) Larson and Cardwell, 1999 [61]; x) USDA, 2002 [62]; y) USDA, 1991 [63]; z) Input 100,000 kcal per kg of herbicide and insecticide; aa) Input 860 kcal per kWh and requires 3 kWh thermal energy to produce 1 kWh electricity; bb) Goods transported include machinery, fuels, and seeds that were shipped an estimated 1,000 km; cc) Input 0.83 kcal per kg per km transported; dd) Average. USDA, 2006; USCB, 2004-2005 [19, 64]

In the U.S. system, the total fossil fuel input is estimated to be 8.2 million kcal/ha (Table 5). The corn yield is also high, about 9,400 kg/ha, or the equivalent of 34 million kcal/ha of food energy. This results in an input:output ratio of 1:4.11.

The fossil energy inputs into U.S. corn production are primarily from oil for machinery and natural gas for fertilizers. Nitrogen fertilizer, which requires natural gas for production, represents the largest single input, about 30% of the total fossil energy inputs (Table 5).

While corn yields are higher in the intensive system than for hand-produced corn, the economic investment is $927/ha, compared with less than $100 per hectare in the hand-produced system (Table 5).

Wheat

Wheat and rice are the two most important cereal crops grown in the world today, and more humans eat wheat than any other cereal grain. Wheat is produced employing diverse techniques with energy sources ranging from human labor, to 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 power (Table 6). Total energy input in this system is about 1.9 million kcal which provides a harvest of about 6.4 million kcal in wheat (Table 6), for an energy input:output ratio of about 1:3.31.

Table 6. Energy inputs of wheat production per hectare in Kenya.

Inputs	Quantity	kcal x 1000
Labor	684 hrs[b,e]	165[d]
Machinery	10 kg[g]	185[c]
Diesel	35 L[g]	350[c]
Nitrogen	22 kg[b]	352[a]
Phosphorus	58 kg[b]	234[a]
Seeds	202 kg[b]	606[c]
Transportation	200 kg[b]	51[c]
TOTAL		1,943
Wheat yield = 1,788 kg[e]		6,437
		kcal input: output = 1:3.31

a) Surendra *et al*., (1989) [65]; b) Hassan *et al*., (1993) [66]; c) Pimentel (1980) [22]; d) Per capita use of fossil energy in Kenya is estimated to be 520 liters of oil equivalents per year based on African data (BP, 2005) [33]; e) Longmire and Lugogo (1989) [67]; f) Kurian (1992) [68]; g) Estimated.

Wheat production in the United States requires more than twice the fossil energy inputs as the low input Kenyan production system (4.2 million kcal) (Tables 6 and 7). Large machinery powered by fossil fuels replaces the animal power and dramatically reduces the labor input from 684 hrs for Kenya to only 7.8 hrs for the U.S. system (Tables 6 and 7). The heavy use of fertilizers and other inputs increased wheat yields to 2,990 kg/ha (Table 7). The input: output ratio in the U.S. for wheat production, approximately 1: 2.57, is lower than that in Kenya.

Table 7. Energy inputs of wheat production per hectare in the United States.

Inputs	Quantity	kcal x 1000
Labor	7.8 hrs[a]	312[d]
Machinery	50 kg[e]	925[e]
Diesel	100 L[b]	1,000[e]
Nitrogen	68.4 kg[c]	1,094[e]
Phosphorus	33.7 kg[c]	143[e]
Potassium	2.1 kg[c]	6[f]
Seeds	60 kg[a]	218[f]
Herbicides	4 kg[a]	400[g]
Insecticides	0.5 kg[a]	5[g]
Electricity	14 kWh[a]	12[e]
Transport	198 kg[a]	67[e]
TOTAL		4,182
Wheat yield 2,900 kg/ha		10,765
		kcal input: output 1:2.57

a) Pimentel and Pimentel, 2008 [5]; b) Karpenstein and Shaeffer, 1998 [69]; c) USDA, 1997 [57]; d) It is assumed that a person works 2,000 hrs per year and utilizes an average of 8,000 liters of oil equivalents per year; e) Estimated; f) FAO, 1999 [28]; g) 100,000 kcal/kg

Rice

Rice is the staple food for an estimated 3 billion people, who live primarily in developing countries. This heavy consumption makes an analysis of various rice production technologies particularly relevant.

Table 8. Energy inputs of draft animal-produced rice per hectare in the Valley of Garhwal Himalaya, India.

Inputs	Quantity	kcal x 1000
Labor	1,703 hrs[a]	2,380[c]
Bullocks	328 hrs[a]	357[a]
Machinery	2.5 kg[b]	5[f]
Nitrogen	12.3 kg[a]	197[d]
Phosphorus	2.5 kg[a]	113[d]
Manure	3,056 kg[a]	5,071[a]
Seeds	44 kg[a]	160[a]
Pesticides	0.3 kg[a]	30[d]
TOTAL		8,313
Rice yield = 1,831 kg[a]		6,591[b]
		kcal input: output = 1: 0.79

a) Tripathi & Sah, (2001) [34]; b) Estimated; c) Per capita fossil energy use in the India is 280 liters of oil equivalents per year (BP, 2005) [33]; d) FAO (1999) [49]; e) The total for fertilizers reported in Tripathi & Sah (2001) [34] was $1.60, we allocated $1.30 for nitrogen; f) Pimentel, (1980) [22] The rice production system practiced by Indian farmers using human labor and bullocks requiring 1,703 hrs of human labor and 328 hrs of bullock labor (Table 8). Energy inputs in this rice system total about 6.6 million kcal. The total rice yield is 1,831 kg/ha (6.6 million kcal), resulting in an energy input:output ratio of about 1: 0.79 (Table 8). This energy ratio could be much higher if the energy for the bullocks were removed from the assessment. This would be a reasonable adjustment, if the bullocks do not depend on fossil energy, but feed on forage and little or no grain.

As in the production of other grains, the United States uses large inputs of fossil energy to produce rice (Table 9). The average yield is 7,616 kg/ha (27 million kcal of food energy). The fossil energy investment is about 19.3 million kcal, resulting in an energy input:output ratio of 1: 1.42 (Table 9). Most of the energy is used for machinery and fuel to replace labor, however, fertilizers account for about 13% of the total fossil energy input. The human labor input of only 11 hrs/ha is much lower than in India, but still is relatively high compared with U.S. wheat production.

Table 9. Energy inputs of rice production per hectare in the United States.

Inputs	Quantity	kcal x 1000
Labor	11 hrs[a]	462
Machinery	38 kg[b]	703
Diesel	373 L[a]	3,730
Nitrogen	161 kg[a]	2,576
Phosphorus	35 kg[a]	156
Potassium	26 kg[a]	94
Seeds	141 kg[a]	560
Irrigation	250 cm[b]	9,877
Herbicides	2.8 kg[a]	280
Insecticides	0.1 kg[a]	10
Electricity	282 kWh[a]	728
Transport	450 kg[a]	150
TOTAL		19,346
Rice yield 7,616 kg/ha[c]		27,418
		kcal input: output 1:1.42

a) Liveszey and Foreman, 2004 [70]; b) Estimated; c) USDA, 2006 [19]

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. Instead, the bean is processed for its oil, and the seed cake and soybean meal are fed to livestock. Soybeans and soy products head the list of U.S. agricultural exports [19].

In the U.S., soybean yields average 2,600 kg/ha to provide about 9.3 million kcal (Table 10). Production inputs total 2.5 million kcal/ha, an input:output ratio of 1:3.71. The largest inputs are machinery and fuel.

Table 10. Energy inputs in soybean production per hectare in the U.S.

Inputs	Quantity	kcal x 1000
Labor	6 hrs[a]	240[b]
Machinery	20 kg[c]	360[d,e]
Diesel	38.8 L[a]	444[f]
Nitrogen	3.7 kg[g]	59[h]
Phosphorus	37.8 kg[g]	156[i]
Potassium	14.8 kg[g]	48[j]
Limestone	2000 kg[o]	562[c]
Seeds	56 kg[a]	450[k]
Herbicides	1.7 kg[a]	170[d]
Electricity	10 kWh[c]	29[l]
Transport	150 kg[m]	16[n]
TOTAL		2,524
Soybean yield 2,600 kg/ha[p]		9,360
		kcal input: output 1:3.71

a) Metzger, 2002 [71]; b) It is assumed that a person works 2,000 hrs per year and utilizes an average of 8,000 liters of oil equivalents per year; c) Pimentel and Pimentel, 2008 [5]; d) Machinery is prorated per hectare and a 10-year life of the machinery. Tractors weigh from 6 to 7 t and harvesters from 8 to 10 tons, plus plows, sprayers, and other equipment; e) College of Agri., Consumer & Environ. Sciences, 1997 [72]; f) Input 11,400 kcal per liter; g) Economic Research Statistics, 1997 [73]; h) Patzek, 2004 [55]; i) Input 4,154 kcal per kg; j) Input 3,260 kcal per kg; k) Pimentel *et al*., 2002 [20]; l) Input 860 kcal per kWh and requires 3 kWh thermal energy to produce 1 kWh electricity; m) Goods transported include machinery, fuels, and seeds that were shipped an estimated 1,000 km; n) Input 0.34 kcal per kg per km transported; o) Mississippi State University Extension Service, 1999 [74]; p) USDA, 2006 [19]

Legumes need less nitrogen than other crops because under most conditions soybeans and other legumes biologically fix their own nitrogen. The biological fixation process carried out by soil microbes uses about 5% of the light energy captured by the soybean plants, but saves the energy that would otherwise be used for nitrogen fertilizer production. Supplying 100 kg per hectare of commercial nitrogen fertilizer to replace the nitrogen fixed by soybeans would necessitate spending 1.6 million kcal of fossil energy. The labor input in the U.S. was only 6 hrs/ha (Table 10), while in the Philippines it is reported to be 744 hrs [20].

Potato

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 [19]. Potatoes contain protein (1.5 to 2.5%), are high in vitamin C and potassium, and offer a good source of carbohydrates.