10 Energy Use in Grain and Legume Production

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

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

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

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

ENERGY INPUTS IN GRAIN PRODUCTION

CORN

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

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

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

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

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

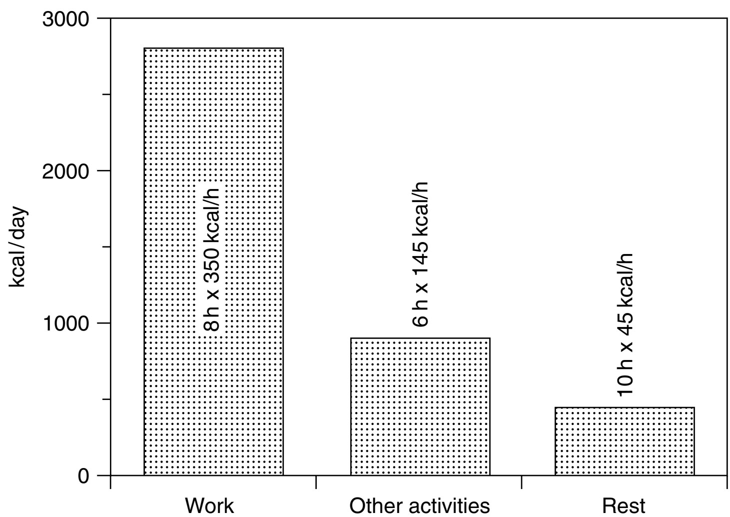

FIGURE 10.1 Total energy expended per adult male in developing countries, in crop-raising activities employing human power only or combined with animal power, is calculated at 4120 kcal per adult male per day.

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

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

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

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

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

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

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

[b] Estimated.

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

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

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

[b] Estimated.

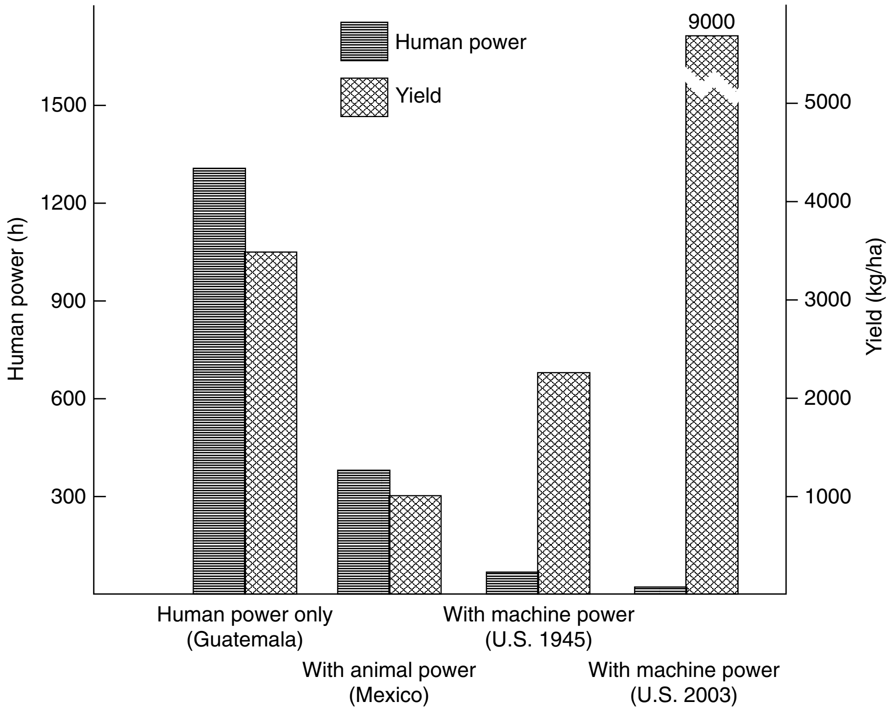

FIGURE 10.2 Human power input and yield per hectare for different corn production systems.

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

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

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

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

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

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

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

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

[c] Estimated.

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

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

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

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

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

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

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

[a] From Stadelman, R., in *Contributions to American Anthropology and History, No. 33*. Carnegie Institute of Washington, Washington, D.C., Publication 523, 1940, 83–263.
[b] Assumed 20,000 kcal of forage consumed per day by ox.
[c] Estimated.

TABLE 10.6
Energy Inputs in Corn Production in the Philippines

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

[a] From AED, *Cost of Production of Corn*. Manila, Department of Agriculture and National Resources, 1960; Food and Agriculture Organization (FAO), *Agriculture: Toward 2000*, Rome, Food and Agriculture Organization of the United Nations, 1981; Allan, P., *Span*, 4, 32–35, 1961.
[b] Assumed 20,000 kcal of forage consumed per day by ox.
[c] Estimated.

TABLE 10.7
Energy Inputs in U.S. Corn Production

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

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

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

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

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

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

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

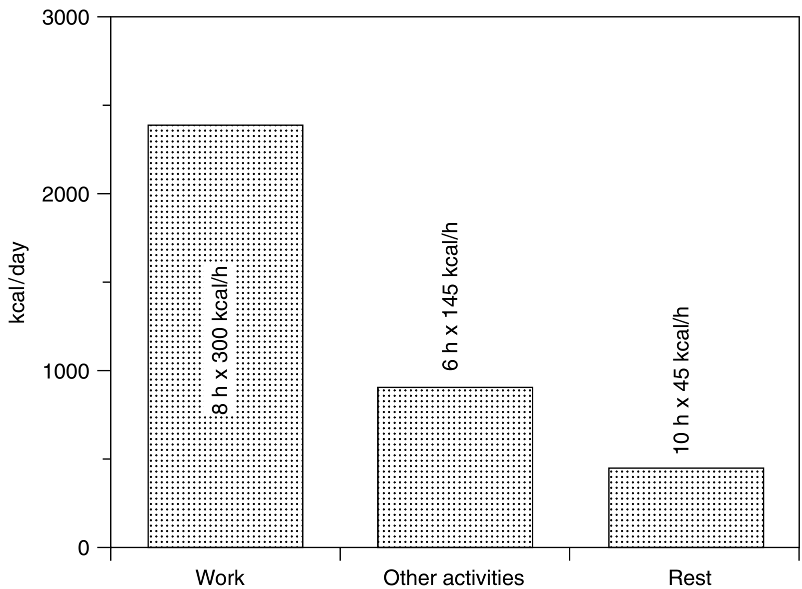

FIGURE 10.3 Total energy expended per U.S. adult male in crop-raising activities employing machinery is calculated at 3720 kcal per day.

WHEAT

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

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

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

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

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

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

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

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

[c] Estimated.

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

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

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

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

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

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

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

Oats

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

Rice

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

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

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

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

[a] From Freeman, J.D., *Iban Agriculture*, London, Her Majesty's Stationery Office, 1955.
[b] Estimated for construction of axe and hoe.
[c] Estimated and direct food energy content of rice used in planting.

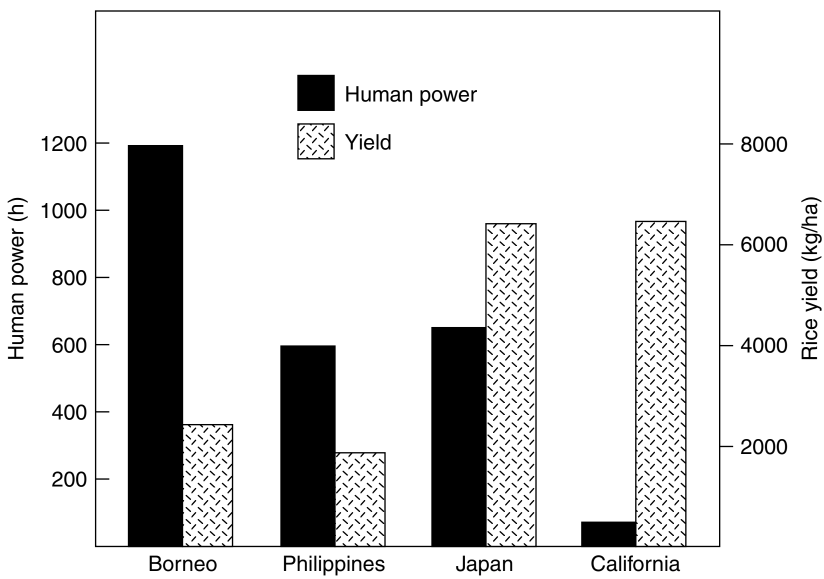

FIGURE 10.4 Human power input and yield per hectare for rice production systems in Borneo (human power only), Philippines (with animal power), Japan (with machine power), and California (with machine power).

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

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

TABLE 10.12
Energy Inputs in Rice Production in Japan

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

[a] Murugaboopathi, C., M. Tomita, E. Yamaji, et al., *Trans. ASAE* 34(5), 2040–2046, 1991.
[b] Hashimoto, K., A.M. Heagler, and B. McManus, *Agricultural Economics and Agribusiness* 106, 1992.
[c] Estimated.
[d] From Allan, P., *Span* 4, 32–35, 1961.
[e] Estimated from Grant, W.R. and T. Mullins, *Arkansas Agricultural Experimental Station Reports Series* 119, 1963.
[f] From U.S. Department of Agriculture (USDA), *Agricultural Statistics 1991*, Government Printing Office, Washington, D.C., 1991.

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

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

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

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

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

[a] From De Los Reyes, B.N., E.V. Quintana, R.D. Torres, et al., *Philippine Agriculture* 49, 75–94, 1965.
[b] Estimated for machinery.
[c] Inputs for carabao were assumed to be similar to that for oxen.
[d] De Los Reyes et al. (1965) valued rice seed at 3700 kcal/kg.
[e] White rice contains 3630 kcal/kg.
Source: Pimentel, D., in *Enciclopedia della Scienza e della Tecnica*, Mondadori, Milan, 1976, 251–266.

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

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

(*continued*)

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

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

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

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

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

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

[b] Estimated.

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

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

Sorghum

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

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

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

[a] Estimated.
[b] An estimated 31.4 tons of machinery is used to manage about 100 ha, and it is assumed that the machinery depreciates over 10 years.
[c] U.S. Department of Agriculture (USDA), *Economic Research Service, Report No. FS–4*. Washington, D.C., 1974.
[d] An estimated 4% of sorghum was irrigated.
[e] Based on U.S. Department of Agriculture (USDA), *Economic Research Service, Report No. FS–4*. Washington, D.C., 1975.
[f] Electrical use was assumed to be 380,000 kcal/h.
[g] From Heichel, G.H., in *Handbook of Energy Utilization in Agriculture*, CRC Press, Boca Raton, FL, 1980, 27–33.
[h] 162 kg × 257 kcal/kg.

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

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

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

ENERGY INPUTS IN LEGUME PRODUCTION

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

SOYBEANS

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

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

TABLE 10.17
Energy Inputs in U.S. Soybean Production

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

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

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

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

Dry Beans

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

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

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

[a] Estimated from soybean data.
[b] Estimated.
[c] Assumed to be similar to U.S. soybean production.
[d] 148 kg × 257 kcal/kg.
[e] From U.S. Department of Agriculture (USDA), *Agricultural Statistics 1976*, Government Printing Office, Washington, D.C., 1976.

TABLE 10.19
Energy Inputs in North-Central Nigerian Cowpea Production

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

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

[b] Estimated.

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

Cowpeas

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

Peanuts

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

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

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

Agricultural Technology

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

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

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

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

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

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

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

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

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

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

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