The Organic Center

Impacts of Organic Farming on the Efficiency of Energy Use in Agriculture

An Organic Center
State of Science Review

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August 2006

I. FOCUS STATEMENT

Each year, the food system utilizes about 19 percent of the total fossil energy burned in the United States (Pimentel et al., 2006) (Figure 1). Of this 19 percent, about 7 percent is expended for agricultural production, 7 percent for processing and packaging, and 5 percent for distribution and food preparation by consumers (Pimentel et al., 2006). If forestry production and utilization are included, the total for the food, fiber, and forestry sectors of the economy rises another 5 percent, to 24 percent of national fossil energy use. This amount of energy (24 percent) is similar to that consumed by automobiles each year in America (USCB, 2004-2005).

The total fossil energy used in U.S. conventional crop production is approximately 1,000 liters per hectare (107 gallons per acre) (Pimentel et al., 2002). Of this, about one-third is for fertilizers, another third is for mechanization to reduce labor, and about a third covers all other activities and inputs, including pesticides. Past studies on energy use in alternative and sustainable corn and soybean production systems have pointed to nitrogen fertilizer and pesticides as the inputs leading to the biggest differences in energy use and efficiency, compared to conventional production systems (Pimentel et al., 2005; Pimentel and Pimentel, 1996).

The high degree of reliance of conventional farming systems on cheap energy became a pressing concern in the wake of rapidly growing oil demand by the U.S., China, and India, and damage to Gulf Coast energy infrastructure in the summer and fall of 2005. In addition, Congress passed a major energy bill in 2005, extending costly subsidies for ethanol production, and dramatically increasing goals for energy production from ethanol and other biofuels, mostly derived from corn. The more than $3-a-gallon gasoline, the war in Iraq, continued instability in the Middle East, and declining global energy reserves in the face of strongly growing worldwide demand, have further elevated the prominence of energy use and efficiency on both the agriculture and energy policy agendas.

Rising energy costs have doubled the cost of many farm inputs and routine farming operations compared to just a year ago, and both fuel and natural gas prices are projected to increase another 30 percent to 50 percent in 2006 (USCB, 2004-2005). Across the country, farmers are deeply worried over energy-driven increases in their production costs. This State of Science Review (SSR) analyzes the extent to which:

- Conversion to organic farming systems will reduce the dependence of farmers on energy; and
- Organic farming can increase the efficiency of energy use per unit of production.

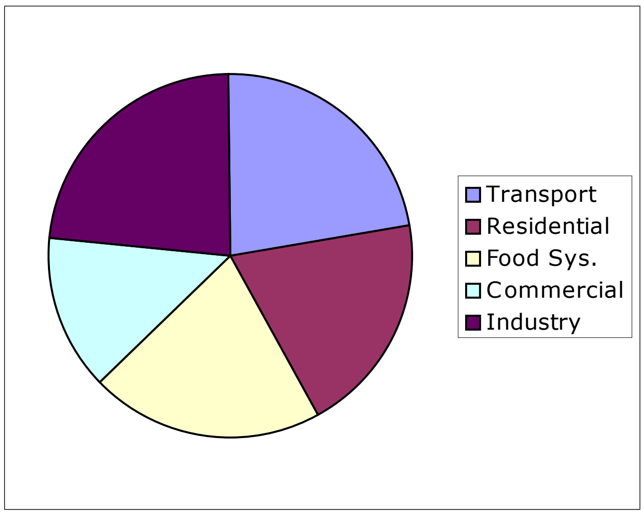


Figure 1. The relative percentages of the approximately 100 quads of fossil energy that is utilized in the United States each year. Note that about 19% is consumed in the food system.

Both organic and conventional farming systems are dependent on fossil and solar energy. In several respects and in carrying out many routine tasks, energy use actually does not differ significantly on conventional and organic farms. The energy cost of trucking grain to market is the same per mile. The same amount of energy is needed to manufacture and run a tractor (these lifecycle costs have been included in the 19 percent above). The energy cost of pumping irrigation water is the same per acre-foot on a conventional and organic farm. The energy tied up in seed, or livestock-breeding stock differs little between conventional and organic farms.

On the other hand, energy use on conventional and organic farms differs substantially in several ways. The largest and most readily measured differences are associated with the energy required to manufacture, ship, and apply pesticides and nitrogen-based fertilizers. Other often-significant differences are harder to quantify and include the impact of organic and conventional farming systems on soil quality and health, and on the conservation of water.

This SSR focuses on the production of corn and soybeans under organic and conventional systems. Data are also presented on the energy inputs in the production of several other major crops grown under conventional systems. The energy inputs in U.S. livestock production systems are also discussed.

Energy Dependence Has Steadily Grown

Yields of most U.S. crops have increased approximately four-fold since the 1940s (USDA, 1940, 2004). Steady yield gains have been the result of technological changes rooted in the breeding of higher-yielding plant varieties, increases in the number of seeds planted per acre, more intensive use of fertilizers and pesticides, and more extensive irrigation of cropland. All of these new production technologies depend on the use of significant amounts of fossil energy.

The availability of ample quantities of fossil energy and new farm technologies has reduced the human labor required to grow and harvest a hectare (2.47 acres) of row crops like corn and soybeans from approximately 1,200 hours per hectare prior to the introduction of farm machinery, to about 11 hours now (Pimentel and Pimentel, 1996; Pimentel and Patzek, 2005).

Comparing labor and energy use across time periods and agricultural systems is tricky. Often, the energy required at a production facility to manufacture a ton of fertilizer is reported as the total energy cost of that fertilizer, ignoring the energy required to ship the fertilizer to the farmer, and the cost of energy embedded in the tanks and equipment needed to handle and apply the fertilizer. In calculating the total energy expended in major crop production on the farm, the additional energy expended by workers who mined and refined the oil, plus that of the workers who made the tractors and other farm equipment, are typically not included.

The energy data for most of the workers who play a role in bringing energy-intensive inputs to the farm remain extremely difficult to obtain. If all human labor that supports conventional farm production is included, an estimated 30 hours of human labor are expended in order to produce a hectare of corn. Even so, the estimated 30 hours of labor are significantly less than the average 1,200 hours expended when corn is raised by hand (Pimentel and Pimentel, 1996).

Peak oil and natural gas supplies are projected for the year 2007, and the resulting decline in energy supplies will change lifestyles and impose economic stresses on all sectors of the economy, including agriculture over several decades

(Youngquist and Duncan, 2003; Campbell, 2005). The decline in fossil energy resources will surely result in increasing prices for fuel, fertilizer, and other essential farming inputs for both organic and conventional farmers.

Both oil and natural gas prices are projected to increase from 30 percent to 50 percent during the year 2006. Economic pressures on farmers triggered by rising energy processes will intensify interest in the identification of farming system alternatives that will consistently increase energy efficiency, and hence reduce the amount of energy needed to produce a given quantity of a particular crop. This SSR highlights the contributions that organic farming practices can make in this quest for more energy-efficient farming systems.

II. MEASURING ENERGY USE AND EFFICIENCY

Plants, humans and other animals, plus microbes, all depend on energy for their survival. Only plants can collect solar energy and convert it into food for their own use. Humans, and indeed nearly all the other organisms on earth, depend on plants, directly or indirectly through animal products, for their energy needs and caloric intake. Adult humans require about 2,500 kcal per day to meet their energy needs.

Plants are not particularly efficient at collecting solar energy; for instance, green plants covering a hectare of land collect on average less than 0.1 percent of the solar energy reaching them. Yet, this is all the solar energy the plant needs to drive photosynthesis and support plant growth, and plants have found ways to adapt to their environment and survive for millions and millions of years. Of course, if plants could collect 100 to 200 times more solar energy each year, their usefulness for capturing and providing needed energy would be greatly enhanced.

On farms throughout the developed world, considerable fossil energy is invested in the course of agricultural production. On average in the U.S., about 2 kcal of fossil energy is invested to harvest 1 kcal of a crop. This high degree of dependence on fossil energy per hectare of crop harvested in America arises more from how food is grown, coupled with the pursuit of ever-higher yields, rather than the inherent physiological dependence of major agronomic crops on energy-based inputs. It also reflects a lack of concern and focus on energy use and efficiency in farm production over the last half century, a period during which most people took for granted, almost as a birthright, ample supplies of affordable fossil energy.

Sound data on energy inputs in crop and livestock production are difficult to find. With crop production, for instance, anywhere from 10 to 15 different energy inputs are required to produce a hectare of a given crop. In addition, it is difficult to find exact energy input values for some inputs in crop production. For example, the exact energy requirements for a specific insecticide, herbicide, or fungicide are difficult or impossible to find in the literature, and thus, average values must be used. Also, some investigators omit certain inputs in crop production, like the energy inputs to produce and repair farm machinery. Farm machinery -- even prorated over several years of service and tens of thousands of acres covered -- still represents a substantial energy need. Indeed, it may account for about 20 percent of the total energy expenditure in crop production.

Additionally, crop-yields vary from state to state. For example, corn yields average about 140 bushels per acre across the entire U.S., but between regions, average from between 46 bushels to 190 bushels per acre (USDA, 2003). These differences influence energy accounting.

Each year, the United States consumes more than twice the amount of fossil energy than the solar energy that is captured by all the plants in the U.S. This includes all the plants in agriculture, forestry, and all other plant-life in the natural environment (Pimentel and Pimentel, 1996). Understanding this relationship is essential because it explains why biomass-based fuels like ethanol and biodiesel, which depend on solar energy, are unable to substitute for finite oil as a transport fuel (Pimentel and Patzek, 2005).

A. Energy Inputs for Organic Corn and Soybean Crops

Organic and conventional corn and soybean cropping systems are addressed in detail in this SSR because these are major crops often grown in rotation on some of the nation's most fertile cropland. Plus, this rotation of crops covers extensive acreage, is energy-intensive, and has been the focus of several studies assessing energy use and efficiency.

Corn: Corn is the major grain crop grown in the U.S. and is the food-energy backbone of the country's food system. It is used primarily to feed livestock, providing 70 percent of livestock feed (USCB, 2004-2005). The manufacture of corn oil, corn syrup, and ethanol are the three other major products derived from corn, although over 200 products are made wholly or in part from corn or the byproducts from corn processing.

Corn is both a high-yield crop and delivers more kilocalories of energy in the harvested grain, per kilocalorie invested in production, than any other major crop. Note the remarkable range in kilocalorie output per unit of input in the production of several crops in Table 1 – from 7.7 in the case of organic corn grown in Pennsylvania, 5.1 for conventional corn, down to 0.26 for conventional tomatoes.

Table 1. A comparison of rate of return in calories per fossil fuel invested in production for major crops. (See tables 2 thru 11 for details on energy outputs per inputs)

		Yield	**Labor**	**Energy**	**kcals**
Crop	Technology	t/ha	hrs/ha	kcal x 10^6	output/input
Corn	Organic[1]	7.7	14	3.6	7.7
Corn	Conventional[2]	7.4	12	5.2	5.1
Corn	Conventional[3]	8.7	11.4	8.1	4.0
Soybean	Conventional[4]	2.7	12	2.1	4.6
Soybean	Organic[5]	2.4	14	2.3	3.8
Soybean	Conventional[6]	2.7	7.1	3.7	3.2
Rice	Conventional	7.4	24	11.8	2.2
Wheat, winter	Conventional	2.7	7.8	4.2	2.1
Potato	Conventional	40.7	35	17.7	1.3
Cabbage	Conventional	27.3	60	11.0	1.3
Orange	Conventional[7]	46.0	210	23.0	1.0
Apple	Conventional[8]	55.0	385	50.2	0.61
Tomato	Conventional	41.8	363	32.3	0.26

1) Average of two organic systems over 20 years in Pennsylvania (Pimentel et al., 2005).
2) Average of conventional corn system over 20 years in Pennsylvania (Pimentel et al., 2005).
3) Average U.S. corn (Table 3).
4) Average conventional soybean system over 20 years in Pennsylvania (Pimentel et al., 2005).
5) Average of two organic systems over 20 years in Pennsylvania (Pimentel et al., 2005).
6) Average of U.S. soybean system (Table 5).
7) Average of Florida orange system (Table 10).
8) Average of eastern apple system (Table 11).

Table 2 estimates the energy inputs and outputs within a typical, or "model" organic corn production system that produces 8,700 kilograms of corn her hectare (130 bushels per acre). Each kilogram of corn contains about 3.58 kcals of energy, or 31,132 kcals from the corn produced on a hectare. A total of 5,377 kcals of energy are required to produce this volume of corn from a hectare, leading to the "harvest" of 5.8 kcal of corn energy per kcal of fossil energy invested in producing the corn (Figure 2) (Table 2). Conventional corn production is somewhat less energy efficient, yielding 4.0 kcal of corn energy per kcal of fossil energy invested (Table 3).

Table 2. Average energy inputs of a model organic corn production system per hectare in the United States employing a vetch cover crop.		
Inputs	**Quantity**	**Kcal x 1000**
Labor	15 hrs	600
Machinery	55 kg	1,018
Diesel	90 L	1,026
Gasoline	40 L	405
Phosphorus	48 kg	200
Potassium	57 kg	186
Lime	1,120 kg	315
Seeds, corn	21 kg	520
Seeds, vetch	14 kg	930
Electricity	13.2 kWh	34
Transport	204 kg	169
TOTAL		5,377
Corn Yield = 8,700 kg/ha		31,132 kcal input:output = 1:5.79

Note that the labor input in the organic corn system, compared to the conventional corn system, was 32 percent greater (Tables 2 and 3). This additional energy cost was offset because of the reduced soil erosion and the reduced loss of phosphorus and potassium nutrients. A comparison of the model organic and conventional system suggests a 31 percent energy saving in the organic system, similar to the 22-year organic and conventional corn system at the Rodale Institute.

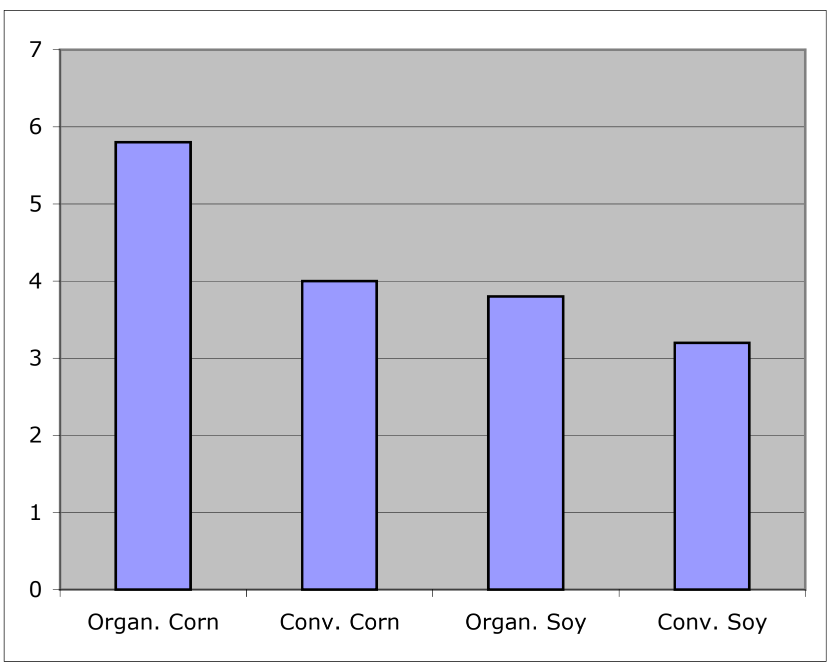


Figure 2. The food energy output (kcal) per fossil energy input (kcal) for organic corn, conventional corn, organic soybean, and conventional soybean.

Table 3. Average energy inputs of conventional corn production system per hectare in the United States.		
Inputs	**Quantity**	**Kcal x 1000**
Labor	11.4 hrs	462
Machinery	55 kg	1,018
Diesel	88 L	1,003
Gasoline	40 L	405
Nitrogen	153 kg	2,448
Phosphorus	65 kg	270
Potassium	77 kg	251
Lime	1,120 kg	315
Seeds, corn	21 kg	520
Herbicides	6.2 kg	620
Insecticides	2.8 kg	280
Electricity	13.2 kWh	34
Transport	204 kg	169
TOTAL		7,795
Corn Yield = 8,700 kg/ha		31,132 kcal input:output = 1:3.99

The 31 percent reduction in energy inputs per hectare of corn on organic farms, compared to conventional production systems, translates into about a 64-gallon fossil fuel saving per hectare for the organic system. If 10 percent of all U.S. corn were grown organically, this would save the nation approximately 200 million gallons of oil-equivalents, or 4.6 million barrels of oil per year. While a significant savings, this represents just 0.06 percent of total vehicle fuel use.

Although the crop yields with corn and soybeans in both the organic and conventional systems were similar, the energy inputs in the two systems were quite different. The organic corn and soybean systems relied on cover crops and/or livestock manure for the required fertilizer nutrients and used no pesticides for production. The conventional corn and soybean systems required commercial fertilizer nutrients and annual applications of usually several pesticides. Thus, both the organic and conventional systems produced about the same food calories, but required different amounts of fossil energy inputs for production.

Comments on the Energy Inputs in Corn Production

Labor- The only labor included in the tables projecting corn energy outputs and inputs was on-farm labor; no attempt was made to include the labor tied up in manufacturing farm machinery, fertilizers, and pesticides. The 11.4 hours of labor per hectare for conventional corn was only a portion of the 2,000 hours that the average farm laborer works each year (Table 3). If a laborer worked exclusively on corn production for 2,000 hours per year, that worker could produce about 175 hectares (433 acres of corn).

How much non-farm energy should be assigned to that worker? The average energy use per person in the U.S. is about 8,000 liters of oil-equivalents per year. This energy represents inputs for roads, schools, police, fire protection and others. It does not include any energy inputs for the family. The worker covering 175 hectares of corn in a year burns about 22,400 liters of gasoline and diesel (128 liters per hectare of corn, times 175 hectares). While a liter of fuel is not equivalent to a liter of oil-equivalent, it is still clear that non-farm energy use by this farm worker accounts for a significant share of on farm use of liquid fuels.

Machinery Operation- The total weight of the machinery was used to calculate the energy required to manufacture the farm machinery. It was assumed that the machinery lasts for 10 years and was used on 160 hectares annually and was prorated accordingly.

Diesel and Gasoline- Mostly diesel fuel was used in the tractors and harvesters. However, some gasoline was also used according to the USDA and others.

Nitrogen, Phosphorus, and Potassium- The application rates per hectare of corn were obtained from the USDA. The energy inputs required to produce a kilogram of each of these fertilizers was based on research by various investigators.

Lime- The application rate of lime per hectare is relatively large, but the energy required to produce a kilogram of lime is relatively small.

Corn Seeds- All corn planted today is hybrid corn and the production is relatively energy-intensive, and the energy data were obtained from the literature.

Herbicides and Insecticides- The average application rates of herbicides and insecticides to corn were obtained from the USDA and other sources. Average energy inputs for the production of these chemicals were used because energy production data for the specific herbicides and insecticides used are not available.

Electricity- Electricity used on a farm was obtained from the USDA. It was assumed that it takes about 3 kcal of fossil energy to produce 1 kcal of electricity.

Transport of Agricultural Goods- Most of the agricultural inputs had the transport energy inputs included, except for machinery, fuels and seeds. It was assumed that these goods were shipped an average of 1000 km.

Soybean: Because of its high protein content (about 34 percent), the soybean is the single most important protein crop grown worldwide. Two-thirds of all soybeans produced are grown in the United States, China, and Brazil. In the United States, very little of the soybean crop is used directly as human food, but instead is processed for oil, while soybean meal is fed to livestock (USCB, 2004-2005). Also, raw soybeans and soybean products are major U.S. agricultural exports (USDA, 2003).

Table 4. Energy inputs for a model organic soybean production system per hectare in the U.S.

Inputs	**Quantity**	**Kcal x 1000**
Labor	9 hrs	360
Machinery	22 kg	360
Diesel	38.8 L	442
Gasoline	35.7 L	270
Phosphorus	24.2 kg	100
Potassium	8.6 kg	28
Lime	1,229 kg	338
Seeds	69.3 kg	554
Electricity	4.8 kWh	14
Transport	135 kg	35
TOTAL		2,501
Soybean yield = 2,668 kg/ha		9,605 kcal input:output 1:3.84

After corn, soybeans produced the most kilocalories of food energy per kcal of fossil energy input (Tables 1 and 4). The model organic soybeans yielded an average of 3.8 kcal of soybeans per kcal fossil energy invested (Figure 2, page 7) (Tables 1 and 4). The conventional soybean production system produced about 3.2 kcal of soybean per kcal fossil energy invested (Figure 2) (Tables 1 and 5). Relatively large quantities of lime were applied to the soybean crop because this crop does best in a soil with a pH of 6 or higher (Troeh et al., 1999; Rehm et al., 2002), whereas little or no commercial nitrogen is necessary (hence the lack of reliance on nitrogen as an input in Tables 4 and 5).

Table 5. Energy inputs in conventional soybean system production per hectare in the U.S.

Inputs	**Quantity**	**Kcal x 1000**
Labor	7.1 hrs	284
Machinery	20 kg	360
Diesel	38.8 L	442
Gasoline	35.7 L	270
LP Gas	3.3 L	25
Nitrogen	3.7 kg	59
Phosphorus	37.8 kg	156
Potassium	14.8 kg	48
Lime	2,240 kg	616
Seeds	69.3 kg	554
Herbicides	1.3 kg	130
Electricity	10 kWh	29
Transport	154 kg	40
TOTAL		3,013
Soybean yield = 2,668 kg/ha		9,605 kcal input:output 1:3.19

B. Energy Inputs for Major Conventionally Grown Crops

Detailed data on the energy inputs in other organic crops are not available, so an energy analysis was made of some other conventionally grown food crops that are important in the United States food system. These include: two grains (rice and winter wheat); two vegetables, (potato and cabbage); and three fruits (oranges, apples, and tomatoes.

Rice: Worldwide, rice is the staple food for about 3 billion people, most of whom live in developing countries. As with the conventional production of other grains in the United States, rice requires large fossil energy inputs of fertilizers, pesticides, irrigation, and machinery for production (Table 6). Average U.S. rice production yielded 2.2 kcal rice energy per 1 kcal of fossil energy invested (Tables 1 and 6).

Wheat: Throughout the world, more wheat is eaten than any other cereal grain produced. Average U.S. wheat production yielded 2.1 kcal of wheat energy per 1 kcal of fossil energy invested. Although the energy inputs for producing conventional wheat are less than those for conventional corn, the wheat yield is low, or less than a third per hectare than corn (Tables 1 and 7).

In part, this is because the production of wheat in the arid regions of the U.S. is low and the energy inputs are also low.

Table 6. Energy inputs and costs of rice production per hectare in the United States.

Inputs	**Quantity**	**kcal x 1000**	**Costs**
Labor	24 hrs[a]	972[c]	$240.00[f]
Machinery	38 kg[a]	742[d]	150.00[g]
Diesel	225 L[a]	2,573[d]	47.25[h]
Gasoline	55 L[a]	558[d]	15.95[h]
Nitrogen	150 kg[b]	2,789[e]	93.00[h]
Phosphorus	49 kg[b]	203[d]	26.95[h]
Potassium	56 kg[b]	183[e]	17.36[h]
Sulfur	20 kg[b]	30[p]	1.00[p]
Seeds	180 kg[a]	772[d]	90.00[i]
Herbicides	7 kg[b]	700[d]	280.00[j]
Insecticides	0.1 kg[b]	10[d]	4.00[k]
Fungicides	0.16 kg[b]	16[d]	6.40[k]
Irrigation	250 cm[a]	2,139[a]	294.00[l]
Electricity	33 kwh[a]	85[a]	2.31[m]
Transportation	451 kg[a]	116[a]	135.30[n]
TOTAL		11,838	$1,403.52
Rice Yield = 7,367 kg[o]		26,522 kcal input:output = 1:2.24	

a) Pimentel & Pimentel, (1996).
b) USDA, (1997).
c) It is assumed that a person works 2,000 hrs per year and utilizes an average of 8,100 liters of oil equivalents per year.
d) Pimentel, (1980).
e) FAO, (1999).
f) We assume that a farm laborer is awarded $10.00 per hour.
g) Estimated.
h) Hinman, et al., (1992).
i) Seeds were estimated to cost 50c per kg.
j) Hinman & Schiriman, (1997).
k) Insecticides and fungicides were estimated to cost $40 per kg.
l) 1 cm of irrigation water applied was estimated to cost $1.18.
m) Price of electricity is 7c per kwh (USCB, 2004).
n) Transportation was estimated to be 30c per kg transported 1,000 km.
o) USDA, (2004).
p) Based on the estimate that sulfur costs 5c per kg (Myer, 1997); it was calculated that the fossil energy input to produce a kg was 1,500 kcals.

Potato: White potato is one of the 15 most heavily consumed vegetable foods in the world. Even in the United States, where a wide variety of vegetables are available, more potatoes are eaten than any other vegetable, or about 22 kg per person per year (USDA, 1998). Equally important, potatoes contain significant calories, protein, and vitamin C.

Although the yield of potatoes averages nearly 41 t/ha, the yield in food energy is 1.3 kcal of energy from potatoes per 1 kcal fossil energy invested, in part because of the 80 percent water content (Tables 1 and 8).

Table 7. Energy inputs and costs of winter wheat production per hectare in the United States.			
Inputs	**Quantity**	**kcal x 1000**	**Costs**
Labor	7.8 hrs[a]	316 [d]	$78.00 [a]
Machinery	50 kg[j]	800 [e]	182.00 [b]
Diesel	49.5 L[k]	565 [e]	10.40 [b]
Gasoline	34.8 L[k]	352 [e]	9.98 [b]
Nitrogen	68.4 kg[c]	1,272 [f]	41.93[b]
Phosphorus	33.7 kg[c]	140 [f]	18.53 [b]
Potassium	2.1 kg[c]	7 [f]	0.65 [b]
Seeds	60 kg[a]	218 [e]	16.77 [b]
Herbicides	4 kg[a]	400 [e]	11.83 [a]
Insecticides	0.05 kg[c]	5 [e]	0.80 [g]
Fungicides	0.004 kg[c]	0.4 [e]	0.20 [g]
Electricity	14.3 kwh [e]	41 [e]	1.00 [h]
Transportation	197.9 kg[i]	123[e]	59.37[i]
TOTAL		4,239	$431.46
Winter Wheat Yield = 2,670 kg[l]		9,035[e] kcal input:output = 1:2.13	
a) Willet & Gary, (1997).			
b) Hinman et al., (1992).			
c) USDA, (1997)			
d) It is assumed that a person works 2,000 hrs per year and utilizes an average of 8,100 liters of oil equivalents per year.			
e) Pimentel, (1980).			
f) FAO, (1999).			
g) It is assumed that insecticides and fungicides cost and average of $40 per kg.			
h) Price of electricity is 7c per kwh (USCB, 2004)			
i) The goods transported include machinery, fuels, and seeds and it is assumed that they were transported an average distance of 1,000 km that cost about 30c per kg. For energy inputs see footnote e.			
j) Estimated.			
k) Pimentel & Pimentel, (1996).			
l) USDA, (2000).			

Cabbage: Cabbage is grown worldwide and is an excellent source of many important nutrients, especially vitamin A, vitamin C, and iron. Cabbage yields 1.3 kcal in food energy per 1 kcal fossil energy invested (Tables 1 and 9). This is a similar yield to that of the potato.

Oranges: Oranges are a nutritious fruit but are very costly to produce, about $3,000 per hectare (Table 10). Although, per hectare, oranges provide more than double the vitamin C content of white potatoes, Americans obtain half of their vitamin C from white potatoes and half from citrus (USDA, 2000). Oranges are not generally consumed for calories but are a favorite source of vitamin C. About 1 kcal in orange energy is obtained per 1 kcal fossil energy invested in orange production (Tables 1 and 10).

Table 8. Energy inputs and costs of potato production system per hectare in the United States.			
Inputs	**Quantity**	**kcal x 1000**	**Costs**
Labor	35 hrs[a]	1,964[d]	$350.00[g]
Machinery	31 kg[a]	574 [e]	300.00 [h]
Diesel	152 L[a]	1,735[e]	31.92[h]
Gasoline	272 L[a]	2,750[e]	78.88[h]
Nitrogen	231 kg[b]	4,294[f]	142.60[h]
Phosphorus	220 kg[b]	911[f]	121.00[h]
Potassium	111 kg[b]	362[f]	34.41[h]
Seeds	2,408 kg[e]	1,478[e]	687.00[h]
Sulfuric acid	64.8[a]	0[i]	73.00[i]
Herbicides	1.5 kg[k]	150[e]	13.50[h]
Insecticides	3.6 kg[k]	360[e]	14.40[h]
Fungicides	4.5 kg[k]	450[e]	180.00[h]
Electricity	47 kwh[a]	135[e]	3.29[j]
Transportation	2,779 kg[c]	2,307[e]	833.70[l]
TOTAL		17,470	$2,863.70
Potato Yield = 40,656 kg[k]		23,296 kcal input:output = 1:1.33	
a) Pimentel & Pimentel, (1996).			
b) USDA, (1997).			
c) A sum of the quantity values for machinery, fuels, and seeds (all converted to mass units).			
d) It is assumed that a person works 2,000 hrs per year and utilizes an average of 8,100 liters of oil equivalents per year.			
e) Pimentel, (1980).			
f) FAO, (1999).			
g) Farm labor costs were estimated to be $10.00 per hour.			
h) Hinman et al., (1992).			
i) Sulfuric acid production is an exothermic process. The cost of sulfuric acid was $73.00/ha. Reference source is cking@micron.net, December 2, 1999.			
j) Price of electricity is 7c per kwh (USCB, 2004).			
k) USDA, (2004).			
l) 30c/kg of goods transported.			

Apples: Apples are another economically valuable fruit crop produced in the U.S., and they cost about $7,725 to produce per hectare (Table 11). Apples are an appetizing fruit and are not produced for food energy. Only 0.61 kcal of apple fruit is produced per 1 kcal of fossil energy invested (Tables 1 and 11).

Tomatoes: Tomatoes are valued for flavor as well as for their vitamin C, vitamin A, and iron. About 42 t/ha are produced but tomatoes are mostly water, about 94 percent. Only 0.26 kcal of food energy is produced per 1 kcal of fossil energy invested (Tables 1 and 12).

Table 9. Energy inputs and costs of cabbage production system per hectare in the United States.

Inputs	Quantity	kcal x 1000	Costs
Labor	60 hrs[a]	2,673[d]	$600.00[g]
Machinery	60 kg[b]	960[c]	200.00 [b]
Fuel	285 L[a]	2,881[a]	71.25[h]
Nitrogen	180 kg[a]	3,346[f]	111.60[i]
Phosphorus	45 kg[a]	186[f]	24.75[i]
Potassium	40 kg[a]	130[f]	12.40[i]
Seeds	4 kg[a]	16[a]	44.00[b]
Herbicides	1.9 kg[c]	190[e]	76.00[k]
Insecticides	2.2 kg[c]	220[e]	88.00[k]
Fungicides	0.4 kg[c]	40[e]	16.00[k]
Electricity	234 kwh[a]	300[a]	16.38[l]
Transportation	249 kg[a]	64[a]	74.70[m]
TOTAL		11,006	$1,335.08
Cabbage Yield = 27,345 kg/ha[n]		13,782	kcal input:output = 1:1.25

a) Data for another cole crop, Brussel sprouts. Pimentel & Pimentel, (1996).
b) Estimated.
c) USDA, (1997).
d) It is assumed that a person works 2,000 hrs per year and utilizes an average of 8,100 liters of oil equivalents per year.
e) Pimentel, (1980).
f) FAO, (1999).
g) Farm labor costs were estimated to be $10.00 per hour.
h) Fuel is assumed to cost 25c/liter.
i) Helsel, (1987).
j) Lime costs 15c/kg.
k) Pesticides were assumed to cost $40 per kg.
l) Price of electricity is 7c per kwh (USCB, 2004).
m) 30c/kg of goods transported.
n) USDA, (2004).

Table 10. Energy inputs and costs of orange production system per hectare in Florida.			
Inputs	**Quantity**	**kcal x 1000**	**Costs**
Labor	210 hrs[a]	9,354[d]	$2,100.00[h]
Machinery	30 kg[a]	480[e]	180.00 [i]
Diesel	90 L[a]	1,096[e]	18.90[j]
Gasoline	96 L[a]	960[e]	27.84[j]
Nitrogen	228 kg[b]	4,239[f]	111.00[b]
Phosphorus	54 kg[b]	224[f]	62.00[b]
Potassium	228 kg[b]	783[f]	49.00[b]
Herbicides	11 kg[b]	1,000[e]	231.00[b]
Insecticides	9 kg[b]	900[e]	103.49[b]
Nematicides	37 kg[b]	3,700[e]	91.00[b]
Electricity	66 kwh[c]	57[a]	4.62[k]
Transportation	500 kg[c]	128[a]	45.00[l]
TOTAL		22,921	$3,024.05
Orange Yield =46,000 kg[b]		23,519	kcal input/output = 1:1.02

a) Estimated.
b) Muraro & Matthews, (1987).
c) Estimated.
d) It is assumed that a person works 2,000 hrs per year and utilizes an average of 8,100 liters of oil equivalents per year.
e) Pimentel, (1980).
f) FAO, (1999).
g) Estimated.
h) Farm labor costs were estimated to be $10.00 per hour.
i) Machinery costs were assumed to be $180.00.
j) Diesel fuel was assumed to cost 21c/liter and gasoline was assumed to cost 29c/liter.
k) Price of electricity is 7c per kwh (USCB, 2004).
l) The cost of transport was assumed to be 30c/kg.

Table 11. Energy inputs and costs of apple production per hectare in eastern United States.			
Inputs	**Quantity**	**kcal x 1000**	**Costs**
Labor	385 hrs[a]	17,150[b]	$3,850.00[d]
Machinery	88 kg[a]	1,408[c]	320.00[d]
Diesel	483 L[a]	5,506[c]	101.43[e]
Gasoline	1,346 L[a]	13,406[c]	390.34[e]
Nitrogen	45 kg[a]	837[j]	27.90[f]
Phosphorus	114 kg[a]	472[j]	62.70[f]
Potassium	114 kg[a]	372[j]	35.34[f]
Herbicides	6 kg[a]	600[c]	120.00[g]
Insecticides	47 kg[a]	4,700[c]	940.00[g]
Fungicides	49 kg[a]	4,900[c]	980.00[g]
Electricity	66 kwh[a]	57[c]	4.62[h]
Transportation	2,974 kg[a]	787[c]	892.20[i]
TOTAL		50,195	$7,724.53
Apple Yield = 55,000 kg[a]		30,660	kcal output/kcal input = 0.61

a) Estimated.
b) It is assumed that a person works 2,000 hrs per year and utilizes an average of 8,100 liters of oil equivalents per year (BP, 1999).
c) Pimentel, (1980).
d) Farm labor costs were estimated to be $10.00 per hour.
e) Diesel fuel was assumed to cost 21c/liter and gasoline was assumed to cost 29c/liter.
f) Hinman, et al., (1992).
g) All the pesticides were assumed to cost $20 per kg.
h) Price of electricity is 7c per kwh (USCB, 2004).
i) Transport of goods was assumed to cost 30c per kg.
j) FAO, (1999).

Table 12. Energy inputs and costs of processing tomato production system per hectare in the United States.			
Inputs	**Quantity**	**kcal x 1000**	**Costs**
Labor	363 hrs[a]	14,580[h]	$3,630.00[l]
Machinery	100 kg[b]	1,600[i]	950.00[a]
Diesel	246 L[c]	2,808[i]	51.66[m]
Gasoline	628 L[c]	6,348[i]	182.12[m]
Nitrogen	200 kg[d]	3,000[j]	124.00[n]
Phosphorus	100 kg[d]	300[i]	55.00[n]
Potassium	150 kg[d]	225[j]	46.00[n]
Lime	50 kg[c]	16[i]	7.50
Seedlings	13,600[a]	100[e]	952.00[a]
Herbicides	1.5 kg[f]	150[k]	60.00[o]
Insecticides	1.5 kg[f]	150[k]	60.00[o]
Fungicides	16 kg	1,600[k]	640.00[o]
Irrigation	125 cm[c]	1,010[c]	251.51[p]
Electricity	77.5 kwh[c]	200[c]	5.43[q]
Transportation	1,024 kg[g]	272[i]	322.20[r]
TOTAL		32,389	$7,337.42
Tomato Yield = 41,778 kg[a]		8,358	kcal output/kcal input = 0.26

a) USDA, (2004).
b) Estimated based on the costs of machinery.
c) Pimentel & Pimentel, (1996).
d) Fertilizer quantities of N, P, and K were estimated based on the total costs of fertilizers.
e) Energy inputs estimated.
f) USDA, (1997).
g) Goods transported were machinery, fuel and seedlings.
h) It is assumed that a person works 2,000 hrs per year and utilizes an average of 8,100 liters of oil equivalents per year (BP, 1999).
i) Pimentel, (1980).
j) Helsel, (1987).
k) Estimated energy inputs based on data from reference i.
l) Farm labor costs were estimated to be $10.00 per hour.
m) Diesel fuel was assumed to cost 21c/liter and gasoline was assumed to cost 29c/liter.
n) The fertilizer input was estimated to cost in total $225 based on data from reference a.
o) All the pesticides were assumed to cost $40 per kg.
p) Estimated.
q)Price of electricity is 7c per kwh (USCB, 2004).
r) Transportation was calculated to cost 30c per kg.

C. Energy Inputs in Livestock Product Productions

Each year, an estimated 45 million tons of plant protein are fed to U.S. livestock to produce approximately 7.5 million tons of animal protein (meat, milk, and eggs) for human consumption (Pimentel, 2004). This includes about 28 million tons of plant protein from grains and 17 million tons from forages fed to livestock. Thus, for every kilogram of high-quality animal protein produced, livestock are fed nearly 6 kg of plant protein (Pimentel, 2004). There are major differences in the inputs of feed and forage in the production of animal products. For example, 13 kg of grain and 30 kg of forage are required to produce 1 kg of beef; 1 kg of pork requires 5.9 kg of grain, whereas 1 kg of broiler chicken requires only 2.3 kg of grain (Figure 3)(Table 13).

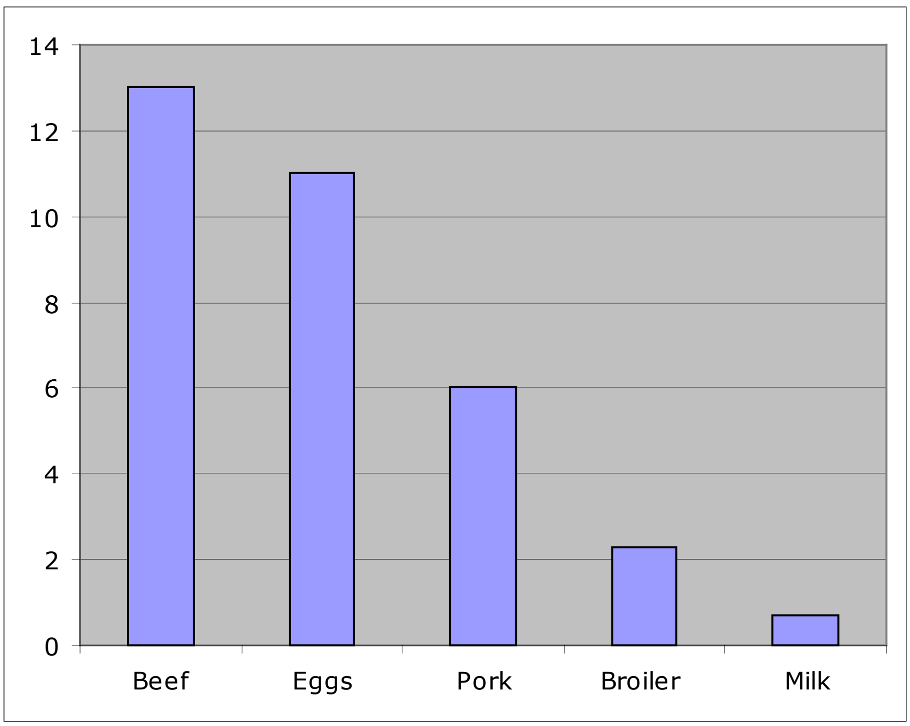


Figure 3. Grain inputs in kilograms per kilograms of livestock products produced.

In the conversion of plant protein into animal protein, there are two principle categories of energy and economic costs: (1) the direct production costs of the harvested animal, including the grain and forage feed; and (2) the indirect costs of maintaining the breeding herd animals.

Either organic or conventional forage can be fed to ruminant animals, like cattle and lamb, because they can convert the forage cellulose into digestible nutrients through microbial fermentation. The total plant protein produced as forage on good U.S. pasture and fed to ruminants is about 60 percent of the amount of protein produced by grains that are fed to animals (Pimentel, 2004). Of course, there is variability between grain and forage crops. The yield per hectare of forage is less than the yield per hectare of grain; and thus, the grass-fed livestock would require more land.

Table 13. Grain and forage inputs per kilogram of animal product produced, and fossil energy inputs (kcals) required to produce 1 kcal of animal protein.

Livestock	Grain (kg)	Forage (kg)	kcal input / kcal protein
Lamb	21	30	57:1
Beef cattle	13	30	40:1
Eggs	11	--	39:1
Grass-fed beef cattle	--	200	20:1
Swine	5.9	--	14:1
Dairy (milk)	0.7	1	14:1
Turkeys	3.8	--	10:1
Broilers	2.3	--	4:1

From: Pimentel, D. 2004. Livestock production and energy use. In, *Encyclopedia of Energy*, Matsumura, R. (ed.), Elsevier, San Diego, CA. pages 671-676.

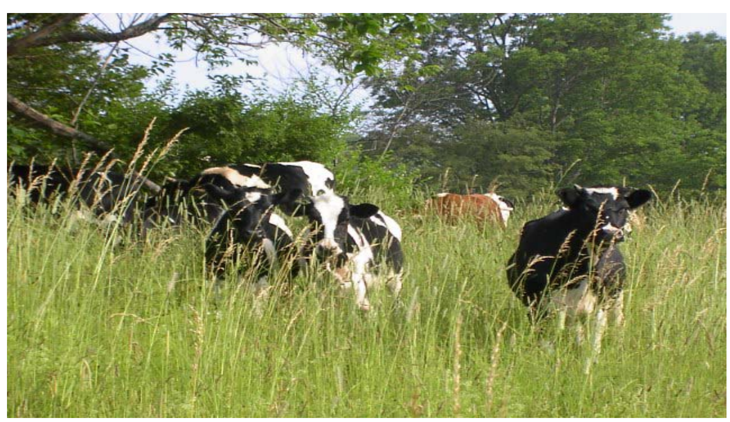
Diverse combinations of grains, forages, and legumes, including soybeans, are fed to livestock to produce meat, milk, and eggs (Tables 1 and 13). The major fossil energy inputs for grain and forage fed to animals include fertilizers, farm machinery, fuel, irrigation, and pesticides. The energy inputs vary according to the particular grain or forage being grown and fed -- as only grain or forage and/or a mixture of grain and forage.

There are many types of hay (dried forage), including grasses and forage legumes. For example, switchgrass, a native grass, is used as livestock forage. It yields about 10 t/ha with the application of fertilizers and when grown on fertile soil (Table 14). This hay provides about 14 kcal in hay feed per 1 kcal invested in fossil energy. Although 10 t is an excellent yield, it is still relatively small when compared to corn, when both the corn grain and corn stover total nearly 18 t/ha.

In the United States, the average protein yield of the major grains (plus soybeans) fed to livestock is about 700 kg/ha. On average, to produce a kilogram of plant protein fed to livestock requires about 10 kcal of fossil energy (Pimentel, 2004).

As mentioned, feeding beef a combination of grain and forage requires 40 kcal to produce 1 kcal of beef protein. However, the production of beef protein on good organic pasture requires one-half as much energy as grain-fed beef production, or only 20 kcal (Figure 4)(Table 13). Clearly, beef animal protein production on good pasture uses significantly less energy than if the animals are fed grain protein, because forage production requires significantly less energy than grain production (Pimentel, 2004).

Of the livestock systems evaluated, conventional and organic chicken-broiler production is the most energy efficient, with 1 kcal of broiler protein produced with an input of 4 kcal of fossil energy (Figure 4) (Table 13). Broilers are a grain-only livestock system. Turkey production is also a grain-only system and is next in efficiency with a 1:10 ratio.



Conventional milk production, based on a mixture of grain and forage feed, also is relatively efficient with 1 kcal of milk protein produced per 14 kcal of fossil energy invested (Figure 4) (Table 13). Although nearly all the feed protein consumed by broilers is from grain, milk production uses about two-thirds grain. Of course, 100 percent of milk production could be produced using hay and/or pasture as feed.

Table 14. Average inputs and energy inputs per hectare per year for hay (switchgrass) production system.			
Input	**Quantity**	**10^3 kcal**	**Dollars**
Labor	5 hr[a]	20[b]	$65.00[c]
Machinery	30 kg[d]	555	50.00[a]
Diesel	100 L[c]	1,000	50.00
Nitrogen	50 kg[e]	800	28.00[e]
Seeds	1.6 kg[f]	100[a]	3.00[f]
Herbicides	3 kg[g]	300[h]	30.00[a]
TOTAL	10,000 kg yield[i]	2,775	$226.00[j]
		40 million kcal yield	input:output ratio = 1:14.4[k]
a) Estimated.			
b) It is assumed that a person works 2,000 hrs per year and utilizes about 8,000 liters of oil equivalents. Prorated this works out to be 20,000 kcals.			
c) The agricultural labor is paid $13.00 per hour			
d) The machinery estimate also includes 25% more for repairs			
e) Calculated based on data from David Parrish (Virginia Technology University), (2005).			
f) Data from Samson, (1991).			
g) Calculated based on data from Henning, (1993).			
h) 100,000 kcals per kg of herbicide.			
i) Samson et al.,(2000).			
j) Brummer et al., (2000). Estimated a cost of about $400.00/ha for switchgrass production. Thus, the $226 total cost is about 56% of the total that Brummer et al. estimate and this includes several inputs not included in Brummer et al.			
k) Samson et al., (2000). Estimated an input per output return of 1:14.9, but have added several inputs not included in Samson et al. Still the input/output returns are similar.			

In a Swedish organic milk production system, 29 percent less fossil energy per unit of milk was used than the conventional milk production system. However, significantly more land was required for the organic system (Cederberg and Mattsson, 2000). Similarly in Denmark, an organic milk production system required 35 percent less fossil energy per unit of milk than the conventional milk production system (Refsgaar et al., 1998). Assuming similar fossil energy reductions in organic milk production in the U.S., based on the Swedish and Demark research, this would reduce the energy inputs required to produce a liter of milk from about 2,000 kcal to about 1,400 kcal of fossil energy.

Both pork and egg production depend primarily on grain feed (Figure 4) (Table 13). Producing 1 kcal of pork protein requires 14 kcal of fossil energy input. In contrast, egg production is relatively costly in terms of feed energy; 39 kcal of fossil energy is expended for 1 kcal of egg protein produced (Figure 4) (Table 13).

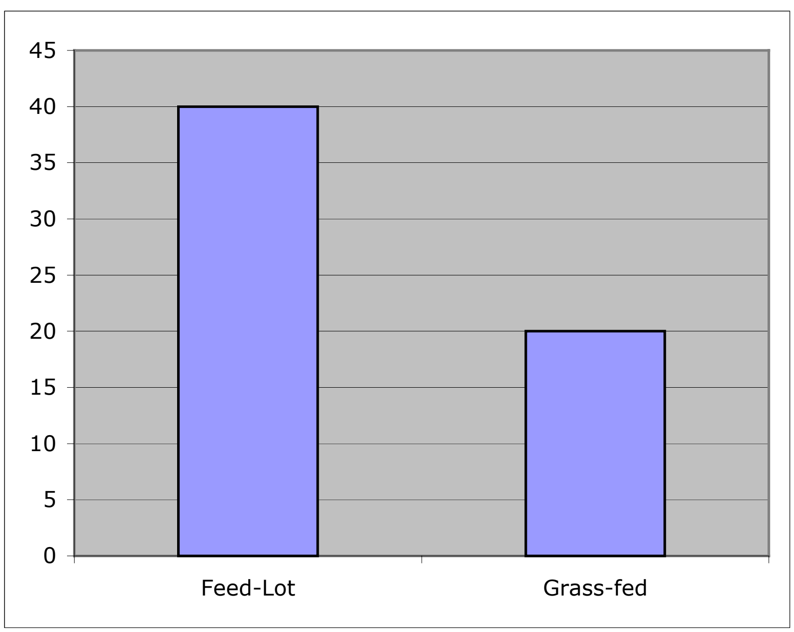


Figure 4. Fossil energy input (kcal) per kcal of beef protein produced in feed-lot compared to organic grass-fed beef.

The two U.S. livestock systems that depend most heavily on forage, but still use significant amounts of grain, are the beef and lamb production systems (Table 13). Based on various combinations of grain and forage, 1 kcal of lamb protein requires an input of 57 kcal of fossil energy; while for 1 kcal of beef, an input of 40 kcal of fossil energy is required. If these animals were fed only on good-quality forage, the energy inputs could be reduced by about half, depending on the nutritional conditions of the pasture forage and the management practices. This result is based on the production of beef fed 200 kg of forage and no grain. The fossil energy input per 1 kcal beef protein in this case required only 20 kcal of energy (Figure 4) (Table 13). Ample rainfall and more land are critical for all productive pasture-forage systems, indeed for all agricultural production.

Under a Swedish livestock production system, organic beef production was less energy costly than conventional beef production, but required significantly more land for production (Kumm, 2002). However, the requirements for additional pasture can be offset by the reduced need for land to grow feed grain.

Based on the analysis of a grass-fed livestock production system in the United States, it was estimated that about half of current animal protein could be produced on forage (Pimentel et al., 1980). In such a grass-fed system, 60 percent less fossil energy was required as well as 8 percent less land. The extra land and energy were used primarily for the production of the grain crops necessary under the regular grain/forage livestock production system.

The fossil energy input for all animal protein production systems analyzed averaged about 25 kcal of fossil energy for each kcal of animal protein produced (Figure 4) (Table 13). This energy input is more than 10 times greater than the average energy input to produce grain protein. As a food for humans, animal protein has about 1.4 times the biological value as a food, compared to grain protein, based on the availability of the essential amino acids.

III. WATER AND ENERGY USE IN CROPS

Past and current rainfall provides all the water required by humans and their managed and natural ecosystems. All plants require water for photosynthesis, growth, and reproduction. Water used by plants is essentially non-recoverable, because some water becomes a part of the chemical makeup of the plant, while the remainder is released as a vapor into the atmosphere. Both the process of carbon dioxide fixation and temperature control require growing plants to transpire enormous amounts of water.

Each year, U.S. agriculture consumes for crop production approximately 80 percent of all the fresh water utilized for various purposes (Pimentel et al., 2004). A U.S. corn crop producing 9,000 kg/ha utilizes about 10 million liters of water (Pimentel et al., 2004).

Worldwide only 17 percent of cropland is irrigated, but this irrigated land produces 40 percent of the world's food (FAO, 2002). In the U.S. about 16 percent of cropland is irrigated and provides 34 percent of the value of all crops produced (USDA, 2003). Irrigation requires an ample source of water plus large amounts of fossil energy, both for pumping and for delivering water to crops. Overall, the amount of energy expended in irrigated crop production is significant (Pimentel et al., 2004).

For example, irrigated wheat requires the expenditure of more than three times the energy needed to produce the same yield of rainfed wheat. Rainfed conventional wheat requires an energy input of only about 4.2 million kcal of energy per hectare per year, while a hectare of irrigated wheat requires 14.3 million kcal per year to supply fossil fuel-based fertilizers and other inputs, plus 5.5 million liters of water (Figure 5) (Pimentel et al., 2004).

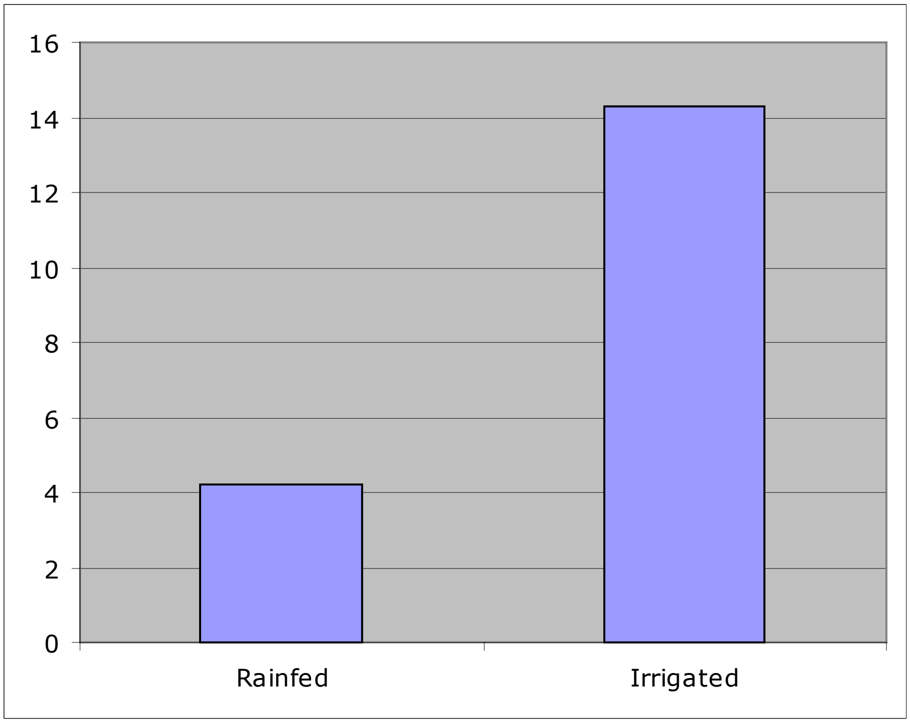


Figure 5. Total fossil energy input (million kcal) per hectare for about the same wheat yield produced under rainfed conditions compared with irrigated wheat.

IV. IMPROVING ENERGY EFFICIENCY IN ORGANIC FARMING SYSTEMS

Soil Organic Matter: Maintaining high levels of soil organic matter is beneficial for all agriculture, but is especially critical on organic farms. On average, the amount of soil organic matter is significantly higher in organic production than in conventional farming.

Typical conventional farming systems with satisfactory soil generally have 3 percent to 4 percent soil organic matter, whereas organic systems soil averages from 5.2 percent to 5.5 percent soil organic matter (Troeh et al., 1999). In the 22-year experiments at the Rodale Institute, the conventional farming system averaged 4 percent, whereas the organic farming systems averaged 30 percent higher, or 5.2 percent (Figure 6) (Pimentel et al., 2005). This high level of soil organic matter in the organic systems is directly related to the high energy efficiencies observed in organic farming systems; organic matter improves water infiltration and thus reduces soil erosion from surface runoff, and it also diversifies soil-food webs and helps cycle more nitrogen from biological sources within the soil.

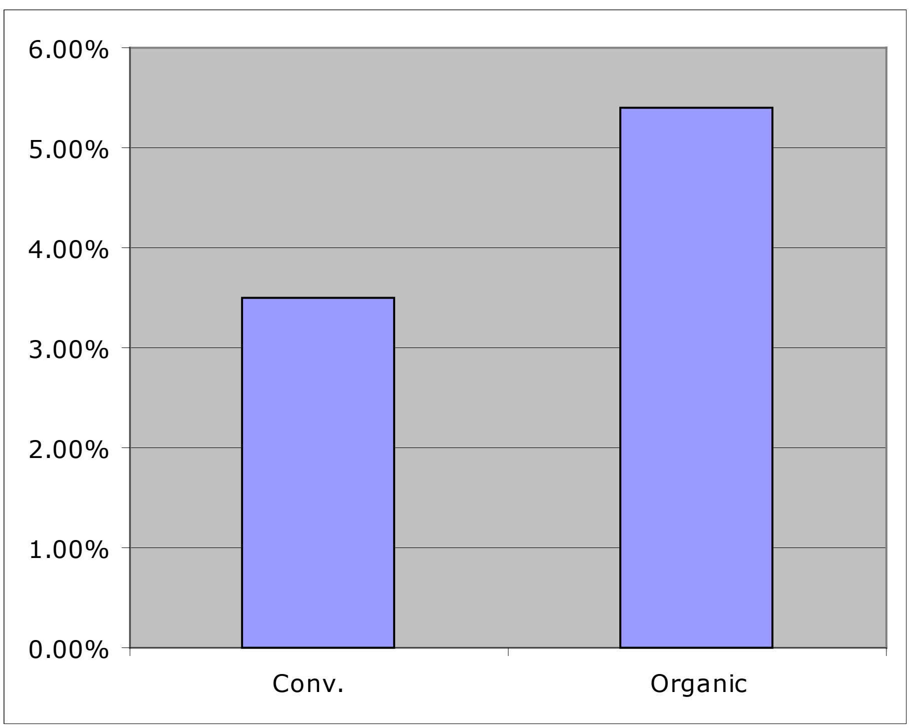


Figure 6. Soil organic matter in the conventional and organic farming systems after the 22-year experiments at the Rodale Institute.

In the Rodale organic farming systems, the amount of organic matter in the upper 15 cm of soil weighed approximately 110,000 kg per hectare (Pimentel et al., 2005). Sullivan (2002) reported that approximately 41 percent of the volume of the organic matter in the organic systems consisted of water, compared with only 35 percent in the conventional systems. The soil in the upper 15 cm of the Rodale experiments was estimated to weigh about 2.2 million kg per hectare. The amount of water held in the Rodale organic system was estimated to be at 816,000 liters per hectare. The large amount of soil organic matter and water present in the organic systems is considered the major factor in making these systems more tolerant of droughts. This was observed in the Rodale organic systems, where corn-yields were about 30 percent higher than those in the conventional corn system during drought years (Figure 7) (Pimentel et al., 2005).

The 110,000 kg per hectare of soil organic matter in the organic corn system could sequester 190,000 kg of carbon dioxide per hectare. This is 67,000 kg more carbon dioxide sequestered than in the conventional corn system. This is the amount of carbon dioxide emitted by 10 cars that averaged 20 miles per gallon and traveled 12,000 miles per year (USCB, 2004-2005).

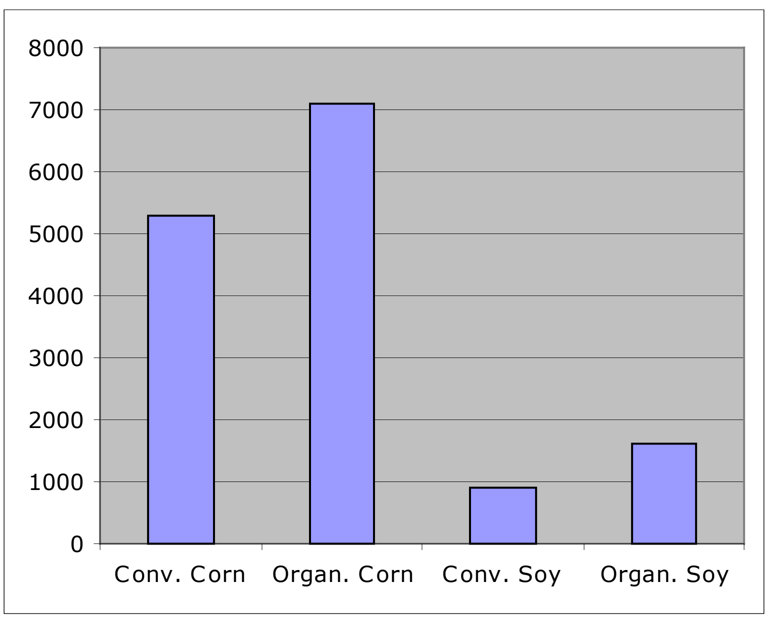


Figure 7. Drought year yields conventional corn, organic corn, conventional soybeans, and organic soybeans (kilograms per hectare per year).

In the Rodale experiments, soil organic (soil carbon) matter was significantly higher in both the organic animal and the organic legume systems than in the conventional system (Pimentel et al., 2005). Soil carbon increased about 28 percent in the organic animal system and 15 percent in the organic legume system, but only 9 percent in the conventional farming system.

Reduced Pesticide Use: Certified organic farming systems apply no synthetic pesticides (Pimentel et al., 2005). Thus, in the 22-year experiments at Rodale, no synthetic insecticides or herbicides were applied in the corn and soybean organic plantings. Weed control in the organic systems was achieved by crop rotations, cover crops, and mechanical cultivation (Pimentel et al., 2005). Obviously, because no herbicides and insecticides were used in the organic farming systems, this improved energy efficiency in the organic systems, when compared to the conventional system.

Weed control with one pass of a cultivator and one pass with a rotary hoe would cost in terms of fossil energy approximately 300,000 kcal/ha. However, with herbicide weed control (6.2 kg/ha of herbicide), plus the sprayer application, this would total about 720,000 kcal/ha, or about twice the energy compared with mechanical weed control.

In general, organic farming systems collect about 1.8 times more solar energy than conventional production systems because most use cover crops. The cover crops growing on the land after the crop is harvested nearly double the amount of solar energy that is harvested per hectare per year. Furthermore, the cover crops also protect the land from soil erosion and water runoff, thereby conserving soil nutrients and water.

Livestock Manure Use: The Rodale organic system that utilized livestock manure represented a typical livestock operation in which grain crops were grown for animal feed, not for cash sale (Pimentel et al., 2005). The rotation used in this Rodale livestock system was more complex than the typical rotation used in the conventional farming system. The Rodale grain-rotation systems included corn, soybeans, corn silage for the cattle, wheat, and red clover-alfalfa hay for the cattle, as well as a rye-cover crop before the corn silage and soybeans were planted (Pimentel et al., 2005).

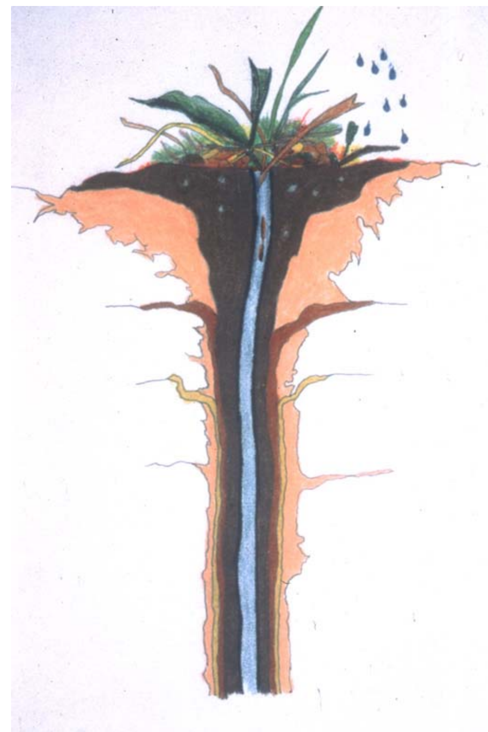
The aged cattle manure served as the soil nitrogen source and was applied at a rate of 5.6 tons per hectare, during two out of every five years. The manure was applied immediately before plowing the soil for planting corn (Pimentel et al., 2005). Additional nitrogen was supplied by the mow-down of the legume-hay crops. The total amount of nitrogen applied per hectare in this manure system was about 40 kg of nitrogen per year (or a total of 198 kg of nitrogen per hectare for any given year with a corn crop).

Crop Rotations and Cover Crops: Crop rotations are beneficial to all agricultural production systems because they help control soil erosion (Troeh et al., 1999; Delgado, 2005). They also help control insect and plant pathogen pests as well as control weeds (Pimentel et al., 1993). They also facilitate the effective use of available soil nutrients (Troeh et al., 1999).

As mentioned, the use of cover crops helps protect the exposed soil from erosion after the main crop is harvested (Troeh et al., 1999). In addition, if the cover crops are legumes, they add essential nitrogen to the soil when plowed under. Cover crops also aid organic agriculture in collecting more solar energy than in a conventional farming system. In addition to soil organic matter, the use of cover crops significantly reduced soil erosion in all the Rodale organic farming systems, compared with the conventional farming systems that used no cover crops (Pimentel et al., 2005). Cover crops that reduced soil erosion and conserved soil organic matter increased the level of soil nitrogen and soil carbon in organic systems compared with conventional systems.

For example, the Rodale organic investigation of nitrogen levels in organic farming systems, compared with a conventional system, confirmed that the soil nitrogen levels in the organic systems were 43 percent for the organic farming systems compared with only 17 percent in the Rodale Institute conventional system (Pimentel et. al., 2005).

Biodiversity and Soil Organic Matter: Abundant soil organic matter is a beneficial characteristic of productive organic farming soils and indeed all sustainable agriculture. This is because soil organic matter is an important source of soil nutrients and also helps increase biodiversity, which provides many essential ecological services including crop protection from pests (Pimentel et al., 2005; Pimentel et al., 1992; Troeh and Thompson, 1993; Lavelle and Spain, 2001; Mader et al., 2002).



For instance, earthworms and arthropods are beneficial in constructing large vertical holes in the soil that facilitate the percolation of water down into the soil. This decreases water runoff and increases water availability for crops. The number of arthropods in organic soils ranges per hectare from 2 million to 5 million, and earthworms from 1 million to 5 million (Blakemore, 2000; Lavelle and Spain, 2001; Gray, 2003). In Denmark, microarthropods and earthworms were reported to be twice as abundant in organic farming than in conventional agricultural systems (Hansen et al., 2001). The biomass weight of earthworms per hectare in agricultural soils can range from 2,000 to 4,000 kg (Lavelle and Spain, 2001). There can be as many as 1,000 earthworm and insect holes per square meter of land in organic farming systems.

The addition of compost and other organics to the soil increases the number of species of microbes present in the agroecosystem (van Elsen, 2000). This significantly reduces crop diseases (Cook, 1988: Hoitink et al., 1991). The Rodale experimental organic systems, which used no synthetic pesticides or commercial fertilizers, resulted in minimizing the harmful effects of agricultural chemicals on soil organisms (Pimentel et al., 2005).

Improved Energy Efficiency in Organic Farming Systems: The two prime factors responsible for the reduced fossil energy expenditures in the Rodale Institute organic systems during their 22-year experiments were: 1) the replacement of the fossil-based commercial nitrogen used in the conventional farming system with legume and/or livestock manure; 2) the reduced use of fossil energy-based insecticides and herbicides in the organic farming systems compared with the conventional farming systems (Pimentel et al., 2005). A third important factor was improved overall management of the soil and nutrients by using cover crops, especially legumes, which not only increased soil nitrogen and organic matter, but also helped conserve water resources throughout the growing season and especially the drought years.

V. CONCLUSIONS

Organic farming systems significantly reduce the fossil energy inputs in production and also improve several aspects of agriculture's environmental performance compared with conventional farming systems.

This SSR reports several key findings:

- Fossil energy inputs in organic corn production were 31 percent lower than conventional corn production, and the energy inputs for organic soybean production were 17 percent lower than conventional soybean production.
- No commercial nitrogen was used in the organic corn and soybean production systems.
- No synthetic pesticides were used in the organic corn and soybean production systems.
- Soil erosion was significantly reduced in the organic production systems compared with the conventional production systems, thus conserving nitrogen, phosphorus, and potassium.
- Water resources were conserved in the organic production systems compared with the conventional production systems.
- Corn and soybean organic farming system-yields during drought years were 30 percent and 50 percent higher than the conventional corn and soybean-yields, respectively.
- Soil organic matter in the organic farming systems was 54 percent higher than in the conventional farming systems.
- The organic corn farming system collected 180 percent more solar energy than the conventional corn farming system.
- The organic beef grass-fed system required 50 percent less fossil energy than the conventional grain-fed beef system.

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ACKNOWLEDGEMENTS

I wish to thank Marcia Pimentel, Cornell University, Ithaca, NY and Anne Wilson, Cornell University, Ithaca, NY for their help with earlier drafts of this manuscript.