Energy Use in American Agriculture

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Summary

Agriculture comprises a significant portion of U.S. energy consumption. Patterns of energy use are influenced by a limited supply of arable land, an increasing population, and a desire by agricultural workers to maintain a high standard of living. These factors along with cheap fossil fuels have encouraged energy intensive farming methods that increase yields and decrease labor intensity at the expense of energy efficiency. This paper describes current patterns of energy consumption in American agriculture, focusing on the most energy intensive processes and suggesting alternative methods that would significantly reduce energy use. Economic and political obstacles to reducing fossil fuel use, and cultural patterns that encourage wasteful practices in the food system are also discussed.

Introduction

Agriculture is often far removed from the minds of most Americans. Requiring large expanses of land, farms are invariably located far from highly populated urban areas. Due to their geographic isolation and possibly a lingering sentimentality for the horse and plough days of old, agriculture is often neglected in discussions of energy consumption and energy efficiency. Modern agriculture, however, is a very energy intensive industry. Food production is currently the fourth largest energy consumer in the U.S. (Pimentel, 1996). Current attempts to decrease fossil fuel consumption, spurred by fears of global climate change or questions of sustainability, would be greatly enhanced by considering the energy consumption patterns of agriculture, where substantial gains in efficiency can be achieved.

This paper will begin by putting current agricultural methods in context, describing briefly how agriculture has evolved and the major factors that have shaped changing patterns of energy consumption. The following sections will attempt to describe the services that energy performs in the U.S. food system, focusing on particularly wasteful practices. A number of alternatives will be suggested along with the economic and political obstacles to change. Finally, cultural preferences for the type, appearance, and availability of the food we eat and their impact on energy use will be examined.

The Modernization of Agriculture

Agriculture exists in a state of continual evolution. From early hunting and gathering societies to modern farms with genetically modified crops, the driving force behind change has remained the same: increasing populations and a scarcity of arable land. It is instructive to briefly examine three major stages of agriculture: hunting and gathering, shifting cultivation, and modern annual crops, and trace how increasing populations and a scarcity in land have influenced the evolution of agricultural methods and their energy intensity.

The earliest methods that mankind used to procure food involved hunting and gathering. In these societies, population densities were very low, with small groups of people following the seasonal availability of nuts, edible plants, and game. Land requirements to sustain this lifestyle were high, estimates range from 40 hectares per person in regions with abundant resources up to 100 km^2 per person in harsher environments (Pimentel, M. 1984, Stout, 1979). Based on the smaller estimate, the U.S. could sustain a population of approximately 20 million. The real figure, however, would be much lower considering the seasonal changes in climate and the unsuitability of some areas for hunting and gathering, probably closer to 10 million. Using a similar estimate, the total world land area (excluding only Antarctica) could support around 300 million people or only 1/20 of the current world population.

Hunting and gathering societies still exist today although most are close to extinction. A study was performed on the !Kung bushmen to determine the energy expended during their daily activities versus the metabolic energy they consume (Lee, 1969). To gather 12.5 kg of nuts with a metabolic energy of 10,500 kcal, they would need to expend 2,700 kcal of energy (including time spent for sleeping and not working). This expenditure amounts to a ratio of output energy to input energy of 4:1. In other words, if we consider the solar energy fixed by photosynthesis of the growing plants as a free source, then the food procurement system of hunting and gathering societies is a net producer of energy.

Hunting and gathering societies most likely developed agriculture gradually to complement their primary food source and did not switch outright to a full reliance on cultivated crops. However, as the food supply increased and allowed for a more sedentary lifestyle, populations also grew. Larger societies could no longer survive by only hunting and foraging and increased their dependence on agriculture. Another pressure acting simultaneously with increasing populations could have been a decrease in the amount of land with sufficient game or edible plants and nuts. Hence, population pressure and a scarcity of land encouraged the transition from hunting and gathering to cultivated agriculture.

An early form of agriculture involved shifting cultivation or Swidden agriculture, in which land was cleared by cutting and then burning the unwanted weeds and vegetation, and then planted and cropped for 2-3 years. Then the land would be abandoned and left fallow for a period of 10-20 years, during which time the soil would accumulate and the cycle would begin again. This style of agriculture required a large input of manual labor, but was sustainable as long as the population density remained around 4 people per hectare (Stout, 1979). A study of the energy flow for human-powered Swidden corn production in Mexico (Pimentel, D., 1984) found an output/input energy ratio of 10.7:1, more than two and half times greater than that achieved by hunting and gathering by the !Kung bushmen. The high energy efficiency in this system is due to the complete dependence on human labor and the fertility of the soil. After burning the vegetation to clear a plot of land, charred plant material decomposes and fertilizes the soil. The nutrient level is therefore higher than it was before the land was cleared, allowing for higher yields than if the land had been left in its natural state. After a few years, most of the nutrients have been removed, yields decrease, and the farmer moves on to a new plot of land.

A further increase in population density again encourages a transition in agricultural methods, this time away from shifting cultivation to annual cropping. The land that previously sat fallow for 10-20 years becomes too valuable to leave idle and farmers must develop techniques to utilize all available land on a more continuous basis. A parallel process that occurs as societies develop is a shift away from subsistence agriculture towards a more integrated cash economy. The challenge in a developed economy that is too large to depend on shifting cultivation consists of increasing the supply of food for a growing population while simultaneously allowing the farmers to achieve a competitive wage relative to workers in non-farming jobs. In the past, farms have accomplished this task by relying heavily on external sources of energy to increase their productivity. The form that this energy will take depends on whether land or labor has a higher opportunity cost. If land is scarce, farmers will focus on increasing the output per hectare of cultivated land and energy inputs will take the form of fertilizers or irrigation if more water is needed. If land is abundant, but labor is expensive then time saving machines will be used to increase the output per hour of manual labor. In some cases, a society may choose both paths, increasing output per hectare and output per hour of labor.

The U.S. is fortunate enough to have an abundance of arable land relative to the size of the population. The total area of farmland in the U.S., defined primarily as agricultural land used for crops, grazing, and pastures, is approximately 370 million hectares, yielding a ratio of 1.4 hectares per person (USBC 1999). This estimate does not include additional land that could be converted into agricultural land if the need arose. The abundance of land in the U.S. and the relatively high wages available outside of the agricultural sector, have encouraged the use of labor saving mechanization to increase output per worker. If there were an excess of farms in the U.S., the incomes of farmers would no longer be competitive with wages available in the city, and the farming population would decrease. In fact, this process has been occurring throughout the mechanization of American farms.

In China, where scarcity of land is a major challenge to feeding the population, the situation is very different. There exists only 0.09 hectares of arable land per person and changes in agriculture have focused on increasing yields per hectare by using large inputs of chemical fertilizer (Giampietro, M. and D. Pimentel, 1994). The standard of living is generally lower in China and increasing the output per worker has not been a major concern. A comparison between the two countries reveals that Chinese farmers currently consume more fossil fuels per hectare of cropland than their American counterparts (Giampietro, M. and D. Pimentel, 1994). This comparison between the U.S.

and China illustrates that energy intensity in agriculture, defined as the energy output/input ratio, is not necessarily proportional to economic development.

The energy inputs into American agriculture are much greater than for either hunting and gathering or the Swidden method. Fossil fuels are used to manufacture fertilizers, pesticides, and herbicides and also to power industrial farm machinery. Vast irrigation networks bring water to semi-arid regions, sometimes over distances of hundreds of miles. These developments have enabled tremendous increases in yields. Corn yields for Swidden corn cultivation in Mexico are around 1,944 kg per hectare, while modern corn production in the U.S. is around 8,500 kg per hectare (USDA, NASS 2000). The large input of energy to achieve these yields means a much lower energy output/input ratio, but not necessarily a lower energy efficiency. The terms energy intensity, energy efficiency, and the energy output/input ratio are often used interchangeably. A more careful definition of each, and the distinctions between them will be helpful at this point.

Energy Efficiency

In the previous section, three stages of agriculture were discussed in terms of their energy output to input ratios, which we will define as the energy intensity. What was not discussed explicitly, however, was a measure of energy efficiency. Definitions of efficiency vary according to context. For the purpose of this paper, efficiency will be defined as an actual work or energy output divided by a theoretical maximum. In the case of agriculture, we can choose the incoming solar radiation as the upper limit for efficiency and the metabolic energy of the harvested plant material as the actual output. The efficiency is simply the percentage of solar energy converted into food. By subtracting all of the energy inputs (e.g. fertilizer, fuel, irrigation, etc.) from the total output and dividing by the 5-month insolation, one can compare the three different methods based on energy efficiency.

$$efficiency = \left(\frac{\sum energy_{outputs} - \sum energy_{inputs}}{insolation} \right)$$

Table 1 Efficiency meausurements for three types of agriculture

Method	**kcal output/input**	**Yield/ha**	**Efficiency**
Hunting and gathering (mongongo nuts)*	3.9:1	1.75 kg	0.0002 %
Swidden corn cultivation**	10.7:1	1944 kg	0.20 %
U.S. corn production***	2.5:1	7500 kg	0.82 %

* From study on !Kung bushmen (Lewis 1969) assuming all nuts were gathered from 1 ha of land
** From study on Mexico Corn Production (Pimentel and Pimentel 1996)
*** Pimentel and Pimentel 1996

Insolation at the earth's surface varies with location and time of day, but a daily average of 1 MW/ha (100 W/m^2) will be appropriate as a basis for comparison. The solar energy reaching one hectare of land accumulated over a 5-month growing season is approximately 3.7 GWhr, or 3.2x10^9 kcal. Table 1 shows the energy efficiency of the three methods of procuring food discussed in the previous section.

The ranking now has now changed and U.S. corn production appears to be the most favorable based on efficiency. This comparison raises an important point. A single efficiency index cannot adequately measure the relative merit of one agricultural system over another. One must judge agricultural methods in the context of the societies in which they exist. Is enough food provided? How much fossil energy is consumed? Do the farmers have a standard of living equal to others in the society? To gain deeper insight into how these questions relate to energy use, the following sections will investigate in more detail the patterns of energy consumption in modern U.S. agriculture.

Energy Use in Agriculture

Energy consumption by the agriculture sector can be broadly categorized into either direct or indirect energy use. Direct energy use refers to the purchase of fossil fuels or electricity to operate tractors, irrigation pumps, drying equipment, refrigeration, other farm machinery, and trucks for transporting the harvested crop. Indirect energy denotes chemical energy in the form of seeds, fertilizers, pesticides, herbicides, and fungicides. The relative contributions to the total energy requirements for corn production are outlined in Table 2. Human power is also included, but in the U.S. it is insignificant relative to the total energy use, representing the smallest input at only 0.05% of the total. While the absolute value of energy inputs will vary depending on the crop, soil conditions, local climate, distance from wholesale distributor, etc., the general categories are similar for most crops grown in the U.S.

Fertilizer

Commercial Fertilizer

The largest energy input by far is in the form of nitrogen fertilizer. As a crop matures, it draws the nitrogen, along with phosphorus and potassium, out of the soil to create new plant material. When 7000 kg of corn is harvested, approximately 40kg of nitrogen, 5 kg of phosphorus, and 6 kg of potassium are taken out of one hectare of land (Pimentel, D. 1984). If this withdrawal were to be replaced directly by chemical fertilizers, it would represent 840,000 kcal, 31,500 kcal, and 15,000 kcal of energy respectively, or 3% of the total energy output from the harvested corn. If the soil is plowed immediately after the harvest and left exposed to wind and rain, as much as 10 times more nutrient may be lost. To prevent yields from declining, this loss in nutrient must be replaced by adding fertilizer. Nitrogenous fertilizer is the most energy intensive to produce and represents the largest input, by mass, of the three types of fertilizer. To produce nitrogen fertilizer, hydrogen is combined with nitrogen to form ammonia, as the following chemical equation illustrates:

$$2N + 3H_2 \quad 2NH_3$$

Table 2   Energy inputs in U.S. corn production

Inputs	Quantity/ha		kcal/ha
Labor	10	h	4,650
Machinery	55	kg	1,018,000
Diesel	75	liters	855,000
Gasoline	40	liters	400,000
Nitrogen	152	kg	3,192,000
Phosphorus	75	kg	473,000
Potassium	96	kg	240,000
Limestone	426	kg	134,000
Seeds	21	kg	520,000
Irrigation	660,000	kg	660,000
Insecticides	2	kg	200,000
Herbicides	4	kg	400,000
Drying	660,000	kcal	660,000
Electricity	100,000	kcal	100,000
Transportation	322	kg	89,000
TOTAL			8,945,650
Outputs			
Corn yield	7,500	kg	26,625,000
Protein yield	675	kg	
kcal output/kcal input			3.0

Source: Pimentel (1996)

The hydrogen is usually obtained by steam reforming natural gas. Ammonia is often combined with CO_2 under pressure at high temperatures to form the solid compound urea, $CO(NH_2)_2$, which is solid at ambient conditions and is therefore easy to handle. Fertilizer use in the U.S. increased fairly steadily up until the mid 1980’s when the average application per hectare began to level off. Figure 1 shows the increase in nitrogen fertilizer use for corn, wheat, and soybeans in the U.S. from 1964 until 1996. Two noticeable dips occur in the early and mid 1970’s, which are most likely consequences of the increase in energy prices during the oil crises. Even though fertilizer is produced using natural gas, volatility in oil prices has a direct effect on its price. This relationship has significant consequences for the sustainability of current fertilizer consumption. Even if the size of natural gas resources remain adequate to sustain current use, a reduction in the availability of oil will increase the price of fertilizer for agriculture as other sectors compensate for dwindling oil reserves by switching their fuel of choice to natural gas.

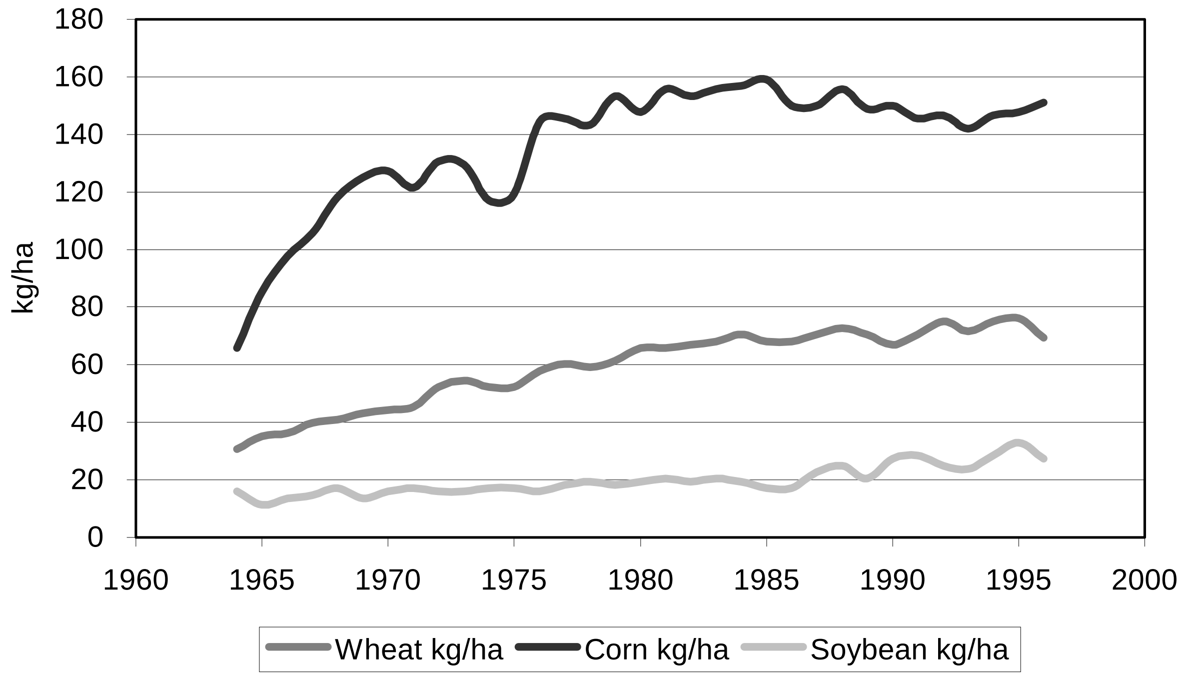

Figure 1 Annual nitrogen fertilizer consumption for various crops. *Source*: USDA, NASS (2000)

Another important limitation to the use of fertilizers is the amount by which they can increase yields. As more and more fertilizer is applied to the land, a point of diminishing returns is reached. Figure 2 shows the relationship between energy intensity and yields per hectare for increasing levels of nitrogen fertilizer in corn production. The results of this study presented by Stout (1984) suggest an optimal fertilizer use at around 225 kg/ha in terms of yield, but only 135 kg/ha of nitrogen for minimum energy intensity. Present day yields for corn have surpassed 8000 kg/ha due to higher yielding breeds and improved farming techniques, but the issue of diminishing returns relative to fertilizer consumption is still present.

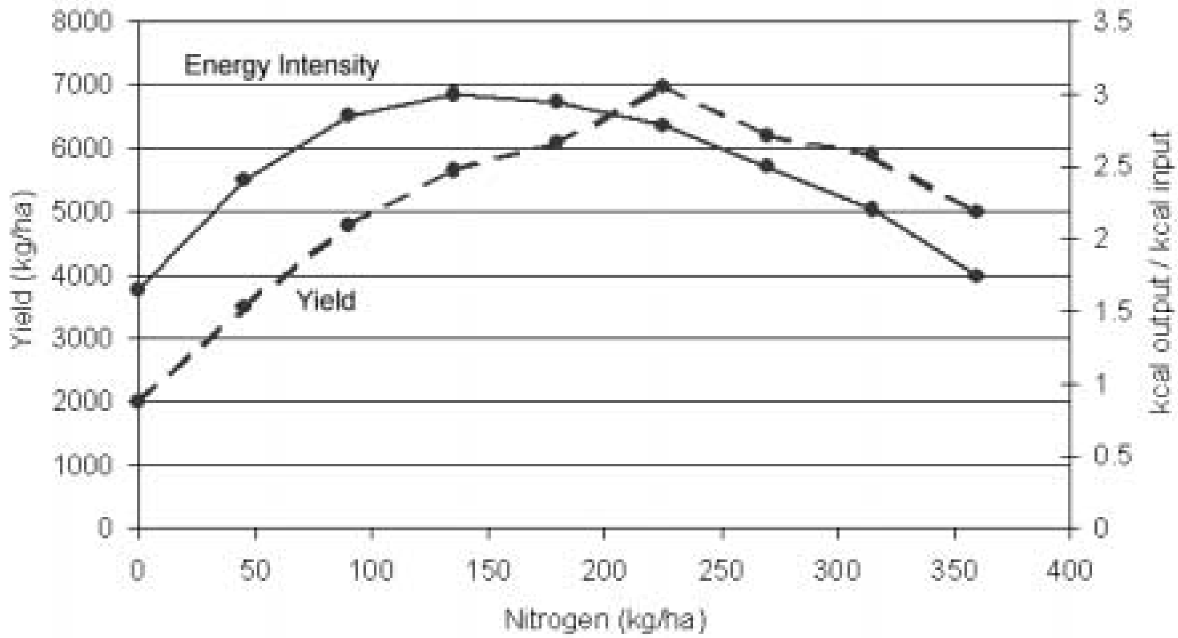

Figure 2 Yields and energy intensity for different levels of fertilizer use on corn. *Source:* Stout (1984)

Referring to figure 1, the current average use of fertilizer for corn crops in the U.S. is around 150 kg/ha, below the level of maximum yield but above the point for optimizing energy intensity. The most important motivation behind the current consumption rate is neither to optimize yields nor to minimize energy intensity, but to maximize profits. Any attempts to change the current system, whether that entails decreasing energy intensity or increasing yields to feed a growing population, will only succeed if the farmer can still maximize his or her profits. With this caveat in mind, we will examine two possible approaches that will decrease energy intensity while simultaneously maintaining or even increasing current yields.

Organic Fertilizers

Replacing nutrients withdrawn from the soil is not limited to the use of chemical fertilizers. Organic fertilizers like manure or crop residues also provide an important source of nutrient. Currently around 1 billion tons of manure and 430 million tons of crop residues are produced annually in the U.S. (Pimentel 1996). The crop residue contains 4.3 millions tons of nitrogen, 0.4 million tons of phosphorus, and 4.0 million tons of potassium, while the manure contains 2.5 million tons of nitrogen, 6,000 tons of phosphorus, and 2,000 tons of potassium (Troeh and Thompson, 1993). Most of the crop residue is recycled (i.e. turned over with the soil) but only 20% of the nitrogen in the manure is returned to the soil, wasting around 2 million tons of "free" nitrogen each year[1]. According to data from the USDA (NASS 2000), the total amount of chemically manufactured nitrogen applied in the U.S. in 1990 was 11 million tons. If all of this manure could be recycled, it would still not be enough to substitute the nitrogen provided by current commercial fertilizer. In addition, the nutrients in manure are not exactly "free." Labor and fuel must be used to collect, transport, and disperse the manure in the field. Along with these disadvantages, however, there exist distinct benefits to increasing scale at which manure is collected and recycled. Minerals not found in inorganic fertilizers that are present in manure improve the soil's ability to hold water, its crumb structure, and its resistance to erosion by water and to crusting in beating rain (Stout, 1984).

Pimentel (1984) calculated the energy savings a farmer could gain by replacing all nitrogen fertilizer with 25 tons of manure per hectare. Assuming the manure has to be transported 1.5 km from the collection site to the field, the total energy consumption to collect, transport and spread the manure is 750,000 kcal. If an equivalent amount of nutrients were provided by commercial fertilizer, the energy requirement would be 2.3 million kcal, an increase by a factor of three. Deciding between using manure or a commercial fertilizer therefore depends on the availability of the manure, the distance it must be transported, and the increase in labor intensity due to its large weight and volume. Table 3 provides a comparison between the advantages and disadvantages of both organic and inorganic fertilizers.

Nitrogen Fixation

Most plants cannot synthesize gaseous nitrogen in the atmosphere but must instead rely on the bacteria in the soil to convert gaseous nitrogen into ammonia or another nitrogen compound that they can absorb through their roots. Some plants form a

[1] The significant amount of nutrient in crop residue that is currently recycled in the field raises questions about the wisdom of collecting it for use as biomass fuel. If crop residues were removed from the field, energy requirements for fertilizer production would undoubtedly increase, not to mention the rate of soil erosion in an exposed field.

Table 3 Comparison of organic versus inorganic fertilizer

Organic	**Inorganic**
Large non-nutrient content	High concentration of nutrients
Bulky	Ease of transport
Little direct cost	Increasing cost
Imprecise content analysis	Made from finite resources
No direct energy use in manufacture	Large direct energy use in manufacture
Readily available	Availability depends on production, cost and region
Provides disposal of wastes	Creates wastes in processing, but can also utilize wastes from other manufacturing processes

Source: Stout (1984)

symbiotic relationship with nitrogen fixing bacteria, enabling them to utilize nitrogen directly from the atmosphere. Nitrogen-fixing symbiotic organisms associated with legumes can easily fix 350 kg of nitrogen per hectare annually (Stout 1984), which is more than two times the amount of commercial nitrogen fertilizer currently used for corn production (see figure 1). Examples of some legumes with this ability include peas, soybeans, alfalfa, clover, and vetch. For this reason, legumes are often planted in rotation with a high yield crop such as corn. After a crop of clover or vetch has matured, it is turned under the soil to recycle the nitrogen. Unfortunately, this method for enriching the soil is often not economical, especially when land is scarce. Every other year a given plot of land will produce no crop for sale. It is often cheaper to buy commercial fertilizer and utilize all of the available cropland every year.

An alternative to crop rotation would be to genetically alter high yielding and financially valuable crops to fix nitrogen from the atmosphere on their own. Transferring the appropriate genetic material from nitrogen-fixing bacteria into the plants themselves is currently the subject of much research. Advances in the field of biotechnology could result in a substantial decrease in the consumption of nitrogen fertilizer, thereby significantly reducing energy requirements.

Machinery

A second major contributor to the high energy intensity of American agriculture is the use of tractors and industrial farm machinery, both in the energy expended for their manufacture and in the gasoline and diesel fuel that they consume. Table 2 shows that machinery, diesel, and gasoline combined account for 25% of the total energy input for corn production, second only to fertilizer at 45%. The heavy use of machinery on U.S. farms is a direct consequence of the high standard of living of most Americans and the relatively expensive cost of labor. Proponents of energy efficiency may suggest reducing the level of mechanization on American farms, thereby increasing labor intensity and reducing yields per worker. Yet this measure would not be feasible on a large-scale without large increases in the price of staple foods. Labor intensive farming methods, like some organic farms, may be able to compete when the product is sold at a premium, but outside of these niche markets labor intensity must remain low for farmers to achieve a standard of living commensurate with workers outside of the agricultural sector.

An interesting comparison can be made between rice production in Japan and in California. Table 4 outlines the energy requirements for each. In both places, the yields per hectare are approximately equal, but values in the labor and fuel requirement differ significantly. In Japan, rice production utilizes manpower to a much greater extent, requiring 640 hours of labor per hectare and only 90 liters of fuel. In California, only 24 hours of labor go into raising one hectare, but 225 liters of diesel and 55 liters of gasoline are consumed. Yields are similar in both regions because of the high use of fertilizer in Japan (slightly greater than in California) and the availability of high yielding varieties of rice in both locations. The labor-intensive system in Japan results in a less energy intensive process with an energy output/input ratio of 2.8, compared to 2.1 in California. This example illustrates that high yields and mechanization are not always related.

Table 4 Comparison between Japan and U.S. rice production

	Japan			California		
Inputs	**Quantity/ha**		**kcal/ha**	**Quantity/ha**		**kcal/ha**
Labor	640	hr	297,600	24	hr	11,000
Machinery	44	kg	860,000	38	kg	742,000
Fuel	90	liters	909,810	280	liters	3,131,000
Nitrogen	190	kg	2,800,000	132	kg	1,945,000
Phosphorus	90	kg	300,000	56	kg	168,000
Potassium	88	kg	140,000			
Zinc				10	kg	49,000
Seeds	112	kg	813,120	180	kg	722,000
Irrigation	90	liters	909,810	250	cm	2,139,000
Insecticies	4	kg	400,000	0.6	kg	60,000
Herbicides	7	kg	700,000	4	kg	400,000
Electricity	2.6	kWhr	7,400	85,000	kcal	85,000
Transportation	300	kg	82,500	451	kg	116,000
Copper Sulfate				11	kg	56,000
Drying				6,500	kg	1,303,000
TOTAL			8,220,240			10,927,000
Outputs						
Rice yield	6,330	kg	22,977,900	6,513	kg	23,624,190
Protein yield	475	kg		374	kg	
kcal output/kcal input			2.8			2.2

Source: Pimentel (1996)

While reductions in mechanization may be difficult, improvements in energy efficiency that do not increase labor intensity are still possible. Many of these improvements can be made through a conscientious effort by the farmer towards energy conservation. Reducing idling time and minimizing total tractor miles can decrease fuel use. The tractors face the heaviest loads while tilling the soil. Primary and secondary tillage prepare the soil for planting by breaking up clods, turning over a cover crop or crop residue, and opening pore spaces to allow water and seed to penetrate. Minimum-till and no-till cultivation are not widely used, but can still achieve high yields under the appropriate conditions and greatly reduce fuel consumption.

Faced with the decision of following conventional soil preparation versus minimum-till methods or other fuel saving alternatives, the farmer will tend to follow the most economical option. Yet, fuel costs are often not the farmer’s primary expense. Table 5 shows data from USDA on costs for the 1998 U.S. corn crop. Fuel costs, which are grouped together with lube and electricity expenditures, account for only 6% of

Table 5 Corn production costs and returns, excluding direct Government payments, 1998

Item	Dollars per acre
Gross value of production	
(excluding direct Government payments):	262.88
Operating costs:	
Seed	30.02
Fertilizer, lime, and gypsum	41.44
Soil conditioners	0.16
Manure	0.51
Chemicals	27.36
Custom operations 2/	11.29
Fuel, lube, and electricity	22.96
Repairs	16.65
Other variable cash expenses 3/	0.31
Interest on operating capital	3.61
Total, operating costs	154.31
Allocated overhead:	
Hired labor	3.19
Opportunity cost of unpaid labor	30.63
Capital recovery of machinery and equipment	66.46
Opportunity cost of land (rental rate)	86.35
Taxes and insurance	7.05
General farm overhead	11.47
Total, allocated overhead	205.15
Total, cash listed	359.46
Value of production less total costs listed	-96.58
Value of production less operating costs	108.57
Supporting information:	
Yield (kg per planted hectare)	8655
Price (dollars per bushel at harvest) 4/	1.91
Enterprise size (planted hectares) 1/	76
Production practices: 1/	
Irrigated (percent)	15
Dryland (percent)	85

1/ For 1996 survey base year only. 2/ Cost of custom operations, technical services and commercial drying. 3/ Cost of purchased irrigation water. 4/ 1 bushel = 25.5kg
Source: USDA (2000) Agricultural Income and Finance - Summary

operating and overhead costs. The rent on the land, capital recovery, labor, fertilizer, and chemicals should be a corn producer's primary concern. Table 5 also illustrates the dismal return on the corn crop for that year. The gross value of production only covered

73% of the total annual cost. One reason for the low value of the crop was a 24% drop in the price of corn from the prior year. This volatility in wholesale prices leads to high uncertainty for the farmer at the beginning of the planting season. Future levels of federal support can also be uncertain (Economic Research Service, USDA 2000). The added risk of experimenting with new cultivation methods or investing in energy saving equipment can often be too much for even the boldest farmers to bear.

Irrigation

Water availability is the primary factor limiting crop production worldwide (Pimentel 1996). Water is essential for all of the photosynthetic and metabolic functions that a plant performs. Without sufficient water, a crop's yield will drop and added nutrients and fertilizer lose their effectiveness. Where rainfall cannot provide an adequate and timely water supply, various forms of irrigation are employed. Postel (1989) estimates that 33% of the world's farmland utilizes some form of irrigation. A number of economic, political, and environmental factors have encouraged widespread use of irrigation in the U.S.

In relatively dry regions, the increase in crop yields for irrigated versus rainfed farmland can be enormous. Current production of rainfed sorghum could increase 67% if irrigation were introduced (Pimentel 1996). In the past, large-scale projects that transport water over long distances have been enabled by the government's policy to subsidize irrigation projects. When the capital cost of constructing an irrigation system is not borne by the farmer, and the price of the fuel used to run the pumps is low, there is a high economic incentive to increase irrigation. In this economic and political climate, irrigation has also been used to save labor costs at the expense of energy efficiency.

All irrigation schemes are not identical. The efficiency of an irrigation project can be measured by its water use efficiency or its energy efficiency. The water use efficiency is defined by the amount of water transpired by the plant plus the evaporation from the soil in the field divided by the total water supplied plus losses resulting from seepage in irrigation canals, leaky pipes, and surface runoff. The energy intensity denotes the amount of energy consumed per unit volume of water transported to the field. A given system can have a high water efficiency, but a high energy intensity, or the converse may be true. For example, a gravity flow system that exploits a drop in elevation from the source may require very little energy input, but may be very inefficient in its water use. If the field is simply flooded, most of the water is wasted as surface runoff. This system could be improved by installing small distribution pipes that supply water selectively over smaller areas to minimize wastage.

Large irrigation projects that transport water long distances or pump from deep aquifers require the largest energy inputs. For example, water from the Colorado River is carried over a mountain range to reach the San Diego River basin at a fuel cost of 185 liters of oil per 1.2 million liters of water. Usually, the energy costs for irrigation are not included in an energy balance for the agriculture sector (Pimentel 1996). In the Western U.S. surface water irrigation costs $40 per million liters, while ground water irrigation costs $140 per million liters (Pimentel, et al., 1996). Total water consumption for U.S. agriculture in 1990 was around 600×10^9 liters, 60% of which came from surface water and the rest from groundwater. At these prices this consumption rate amounts to $48 million per year. Taking a different approach, one can look at the average water requirements to grow a particular crop. In California, producing 1 kg of corn requires 1400 liters of water, rice needs 4700 liters, and to grow the feed grain for 1 kg of beef uses up to 8300 liters of water (Pimentel, 1996). If this water originated from groundwater, the added price per kg would be $0.20 for corn, $0.66 for rice, up to $1.16 for beef. Ending government subsidies of irrigation to encourage water conservation would be practically impossible for any politician to pass.

The most effective way to increase energy efficiency in irrigation is to increase water use efficiency. A vegetative cover on farmland and the surroundings can greatly reduce water runoff. Leaving organic matter on the soil, like crop residues, reduces the impact of raindrops in heavy storms, which tends to compact the soil and also leads to runoff and erosion. Organic material within the soil maintains the soil's structure allowing for water droplets to percolate down from the surface. Finally, choosing crops appropriate for the local climate can also lessen the reliance on irrigation. If the farmer lives in a water scarce region but does not pay for irrigation, he or she may choose the highest value crop regardless of its water needs. A more water efficient and energy efficient choice would be a crop with a low water requirement, like cabbage or wheat.

The Food System

The previous three sections have focused on three major energy inputs: fertilizers, machinery, and irrigation. The motivation behind current practices in each of these processes was shown to be economic. Historically cheap sources of energy have encouraged farmers to invest in chemicals, machinery, and irrigation systems that reduce labor intensity and increase output, sometimes at the expense of energy efficiency. However, if prices begin to reflect the environmental damage inflicted by a heavy reliance on fossil fuels or fluctuate due to uncertainty in their supply, economic forces could just as easily push agriculture towards higher energy efficiency. The larger food system, which includes distribution to the consumer, food packaging and preparation, and cultural choices in diet, are not as readily controlled by economics.

Figure 3 shows an energy flow diagram for the entire food system in the U.S., starting with the solar energy required to produce one kilocalorie of food. The inputs to the system during the production stage are 16 kcal of solar energy captured in plant material and 1.39 kcal from machinery, drying, irrigation, field operations, petroleum, and chemicals. Excluding the crop residue and fiber products, the energy of the edible material produced is 11 kcal, yielding an energy output/input ratio of 11 / 1.39, or 7.9, which is very high compared to the examples presented previously. The lower half of the diagram shows that most of the crops produced end up as animal feed, and only around 6% are eaten directly by humans. Of the total kilocalories in the animal feed, only 3.7% end up in the final animal products. While most of the animal feed originates from crops that are not edible for humans, it still requires land and energy that could otherwise be used to produce grains and vegetables that are edible. This diversion of a large portion of vegetable food away from human consumption represents an extremely inefficient way for humans to obtain enough kilocalories in their diet. It is also a luxury afforded only by societies wealthy enough to produce grain and feed in abundance.

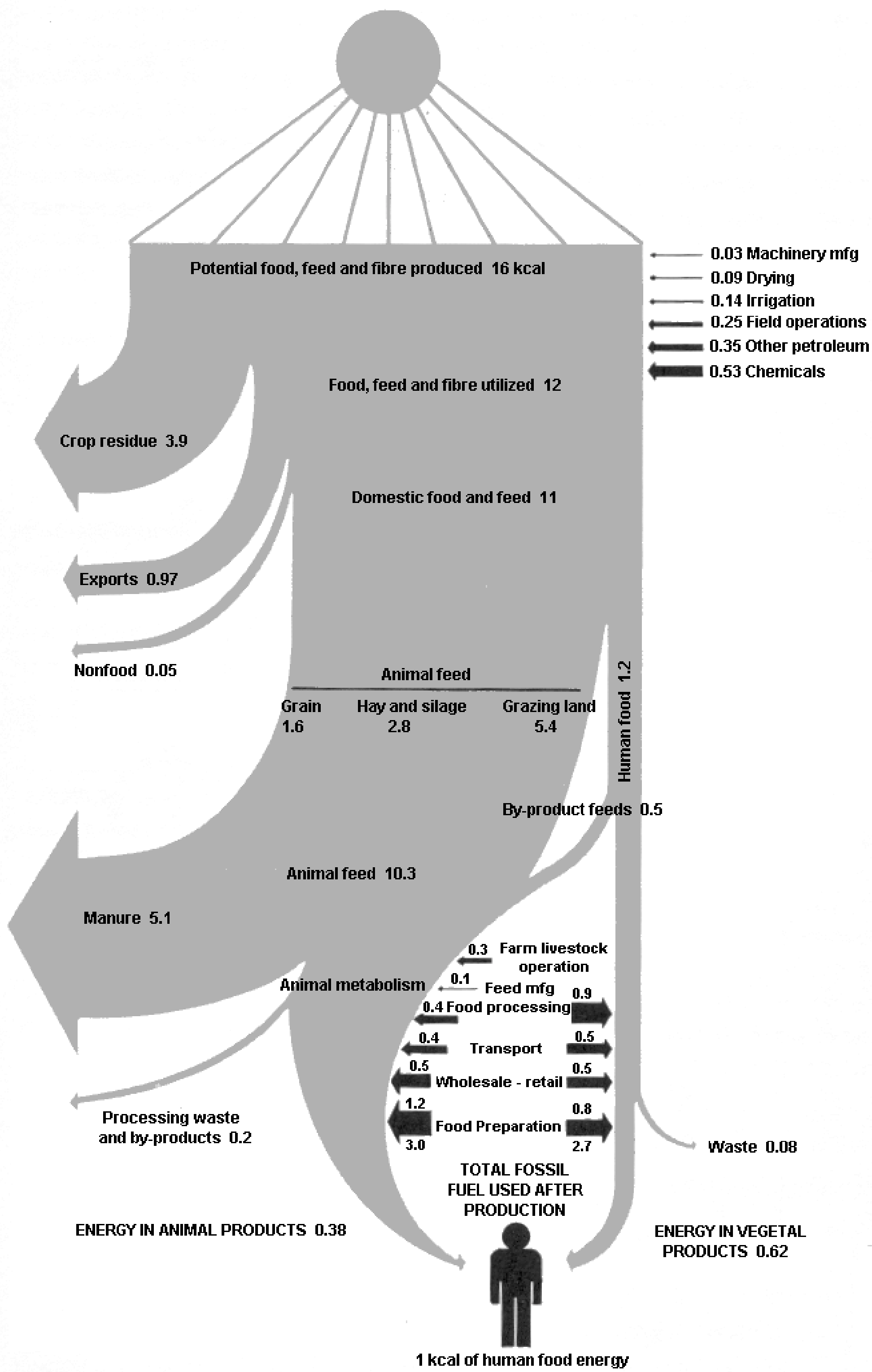

Figure 3 Energy flow for the U.S. food system. *Source*: Stickler (1975)

Table 6 compares the average diet in the U.S. with other developed countries and with China. The U.S. is only slightly above the other MDCs in terms of meat consumption with 28% percent of kilocalories coming from animal products (significantly less than the 38% shown in figure 3). In China, however, most people obtain only 17% of their daily kilocalories from animal products. Table 6 also shows that Americans on average eat 14% more than people from the developed nations and 31% more than the Chinese. For the U.S., these consumption patterns on the demand side of the food system are difficult to control. It is hard to imagine anyone effectively leading a movement of vegetarianism in the name of energy efficiency, even though this would have a greater impact on reducing energy consumption (and water consumption) than any of the measures previously mentioned. For example, using the data provided by Stickler (1975) on energy requirements for meat production, we can calculate the amount of energy saved if all Americans were to switch to a totally vegetarian diet and all feed crops were replaced with crops edible for humans. With a 100% vegetarian nation, 1.3 kcal would be conserved for every kcal of food produced compared to a national diet consisting of 38% animal products and 62% vegetable products[2]. This change would represent an energy savings of 4.5×10^{14} kcal, or 1.8 quads. The high calorie and animal intensive American diet also raises ethical questions on whether or not the current abundance of cheap food in the U.S. is justifiable while people in other regions of the world go hungry. Debates on international food security are entrenched in the politics and economics of international trade and aid, and are beyond the scope of this paper.

In addition to the large diversion of plant crops for animal feed, another gross inefficiency on the post-production side comes from the transportation and cosmetic packaging of food products. For each kilocalorie of vegetable products alone, an additional 2.7 kcal are used for processing, transport, packaging, and preparation. With animal products, 3 kcal are added after production of the feed for every 1 kcal consumed. Including all of the energy inputs, from fertilizers to food preparation (but not including solar energy), 7.1 kcal are consumed to produce 1 kcal in a diet consisting of 38% animal products and 62% vegetable products. The energy output/input ratio no longer favors

[2] In Stout's analysis 41% of the human food stream is diverted as by-product feed. The calculation for the vegetarian nation assumes, conservatively, that an equivalent percentage is still diverted.

Table 6 Average Daily Food Calorie Supply in the USA, MDCs, and China, 1994-96

	kcal per Person per Day					
	kcal			in % of total		
	USA	**MDCs**	**China**	**USA**	**MDCs**	**China**
Grand total	3,624	3,183	2,766	100	100	100
Vegetable products	2,618	2,316	2,306	72	73	83
Animal products	1,006	867	461	28	27	17
Cereals (excl. beer)	851	1,009	1,646	23	32	60
Starchy roots	103	137	154	3	4	6
Sweeteners	640	396	71	18	12	3
Pulses	35	27	15	1	1	1
Vegetable oils	546	366	128	15	11	5
Vegetables	71	67	98	2	2	4
Fruits (excl. wine)	123	93	42	3	3	2
Alcoholic Beverages	158	149	82	4	5	3
Meat	428	332	320	12	10	12
Animal fats	123	152	35	3	5	1
Milk	373	279	15	10	9	1
Eggs	51	47	52	1	1	2
Fish, seafood	29	46	29	1	1	1
Other	93	83	79	3	3	3

Source: Heilig, (1999)

the output side, and now the food system is a net *consumer* of energy. For certain products, the ratio is even more extreme. A 0.5 kg head of lettuce with a metabolic energy of 50 kcal, transported 4,827 km from California to New York, requires 1800 kcal of fossil energy, more than 36 times the energy contained in the lettuce (Pimentel, 1984). A diet soda with only 1 kcal is packaged in an aluminum can that required 1600 kcal to produce. This estimate does not include the 600 kcal needed to process the 12 oz soda, bringing the total to 2200 kcal for 1 kcal of soda (Pimentel, 1984). Obviously, people drink diet soda for reasons other than obtaining calories. However, these examples illustrate the cultural apathy concerning the energy consumption in transporting and packaging everyday foods.

The consumer also pays a financial price for the post-production side of the food system. Only 21% of total consumer food expenditures in 1997 paid for the farm value of the food, while the remaining 79% went towards the market bill, which includes non-farm labor, transport, packaging, advertising and other costs (USBC, 1998).

Table 7 Energy needed to transport 1 kg 1 km

Transport System	**kcal/kg/km**
Barge	0.1
Rail	0.32
Truck	1.2
Air	6.36

Source: Pimentel (1996)

The conglomeration of smaller farms into larger industrial farms provides both an opportunity for more efficient food transport and a danger of excessive transport. Between 1980 and 1998 the number of farms in the U.S. has decreased from 2.44 million to 2.192 million and the average acreage per farm has increase from 426 to 435 acres. If food products originate from fewer or more concentrated locations, high capacity and more efficient means of transport can be utilized. Table 7 shows the cost to transport 1 kg of food 1 km by way of truck, rail, barge, or air. Using barge transport is clearly the most energy efficient method, although it is limited to locations accessible by waterway and situations when the longer travel times are not important. Rail transport, which is more accessible than barge, is around 3 ¾ times more energy efficient than by truck. Thor and Kirkendall (1982) estimate that 41% of agricultural goods are transported by truck, 40% by rail, and 19% by barge. If the food producing regions have more extensive access to rail or barge, energy savings could be significant.

Along with the advantages of fewer and higher producing farms, comes the temptation for excessive long distance food transport. Consumers, no longer bound by the seasonal variations of their local farms, demand strawberries in winter and fresh tomatoes year round. This trend has encouraged situations like the previous example where a 50 kcal head of lettuce requires 1800 kcal to travel from California to New York. These evolutionary patterns in agriculture are extremely difficult to combat, as they reflect increases in convenience for the consumer and a higher concentration of influence among fewer food producers. Restructuring the agricultural sector towards smaller and more distributed farms could be encouraged by the lower cost for transportation, but would certainly result in higher prices paid for the farm value of the food. According to

Table 8 Energy Required to Produce Various Food Packages

Package	kcal
Wooden berry basket	69
Styrofoam tray (size 6)	215
Moulded paper tray (size 6)	384
Polyethylene pouch (16 oz or 455 g)	559
Steel can, aluminum top (12 oz)	568
Small paper set-up box	722
Steel can, steel top (16 oz)	1,006
Glass jar (16 oz)	1,023
Coca-Cola bottle, nonreturnable (16 oz)	1,471
Aluminum TV dinner container	1,496
Aluminum can, pop-top (12 oz)	1,643
Plastic milk container, disposable (1/2 gallon)	2,159
Coca-Cola bottle, returnable (16 oz)	2,451
Polyethylene bottle (1 qt)	2,494
Polypropylene bottle (1 qt)	2,752
Glass milk container, returnable (1/2 gallon)	4,455

Source: Pimentel (1996)

the USBC (1999) the percentage of total consumer food expenditures allocated for transportation in 1998 was 4.2%. It is questionable whether or not the lower cost of transportation for distributed farms would enable them to compete with large industrial farms.

In addition to transportation, the energy requirements to package food products are also considerable. Energy consumption varies greatly with the particular food product. A 1 kcal diet soda in an aluminum can provides an example of extremely energy intensive packaging, while fresh produce may require little energy at all to package. Table 8 lists a number of different types of packaging and their according energy requirement. Some packaging choices are guided by safety and hygiene, but as any consumer knows, aesthetic considerations play an equally important role. For example, aluminum is commonly used to produce thin-walled and lightweight soda cans even though steel cans, which would provide an equally refreshing product, require only one-third of the energy to produce. To the consumer, however, a steel soda can would appear heavy and bulky, with a consistency probably resembling motor oil instead of soda. Even if material prices rise, it may be very difficult to switch consumers away from familiar packaging. In 1998, packaging represented 8.7% of consumer expenditures on food, the highest single component outside of labor and on-farm production costs (USBC 1999). Essentially, consumers will pay more for a product if it looks appealing.

Conclusion

Energy use in agriculture has developed in response to increasing populations, a limited supply of arable land, and a desire for an increasing standard of living. In all societies, these factors have encouraged an increase in energy inputs to maximize yields, minimize labor-intensive practices, or both. In the U.S, the availability of land has been less restrictive than the opportunity cost of labor, resulting in large investments in time saving machinery. Cheap supplies of fossil fuels have encouraged the production of inexpensive fertilizer to augment yields, further mechanization, and extensive and costly irrigation systems. The efficiency and energy intensity of each of these inputs has not been optimized due to the lack of sufficient economic incentives and, in the case of irrigation, current government policy. A number of feasible alternatives are possible that could reduce energy use without decreasing yields or increasing labor intensity.

After food products have left the farm, the energy requirements for post-production processes are especially wasteful. Due to high consumer expectations, food is inefficiently transported over long distances throughout the year. The distribution system is currently organized in favor of truck transport although barge and rail are much more efficient. Food packaging can be extremely energy intensive, but consumer habit makes any changes towards higher efficiency very difficult. Finally, energy use in American agriculture should not be discussed without proper consideration of the American diet. The high percentage of calories obtained from animal products requires the production of large amounts of feed and leads to an inefficient utilization of cropland.

As the U.S. population continues to rise, the agriculture sector will not break down in the near future from a lack of energy. However, reducing the dependence on fossil fuels will gain in importance as efforts continue to reduce GHG emissions and as fuel supplies eventually do dwindle. Fortunately, the development of alternative farming methods and advances in biotechnology will likely achieve this end.

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