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Food Versus Biofuels: Environmental and Economic Costs

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Abstract The rapidly growing world population and rising consumption of biofuels intensify demands for both food and biofuels. This exaggerates food and fuel shortages. The use of food crops such as corn grain to produce ethanol raises major nutritional and ethical concerns. Nearly 60% of humans in the world are currently malnourished, so the need for grains and other basic foods is critical. Growing crops for fuel squanders land, water and energy resources vital for the production of food for human consumption. Using corn for ethanol increases the price of US beef, chicken, pork, eggs, breads, cereals, and milk more than 10% to 30%. In addition, Jacques Diouf, Director General of the UN Food and Agriculture Organization, reports that using food grains to produce biofuels is already causing food shortages for the poor of the world. Growing crops for biofuel not only ignores the need to reduce fossil energy and land use, but exacerbates the problem of malnourishment worldwide.

Keywords Agriculture · Biofuels · Energy · Food security · Fossil fuels · Natural resources · Renewable energy

Introduction

With global shortages of fossil energy, especially oil and natural gas, and heavy biomass energy consumption occurring, a major focus has developed worldwide on biofuel production (Barbara 2007). Emphasis on biofuels as renewable energy sources has developed globally, including those made from crops such as corn, sugarcane, and soybean. Wood and crop residues also are being used as fuel (Pimentel and Pimentel 2008). Though it may seem beneficial to use renewable plant materials for biofuel, the use of crop residues and other biomass for biofuels raises many environmental and ethical concerns (Pimentel 2006).

Diverse conflicts exist in the use of land, water, energy and other environmental resources for food and biofuel production. Food and biofuels are dependent on the same resources for production: land, water, and energy. In the USA, about 19% of all fossil energy is utilized in the food system: about 7% for agricultural production, 7% for processing and packaging foods, and about 5% for distribution and preparation of food (Pimentel *et al.* 2009). In developing countries, about 50% of wood energy is used primarily for cooking in the food system (Nonhebel 2005).

The objective of this article is to analyze: (1) the uses and interdependencies among land, water, and fossil energy resources in food versus biofuel production and (2) the characteristics of the environmental impacts caused by food and biofuel production.

Food and Malnourishment

The Food and Agricultural Organization (FAO) of the United Nations confirms that worldwide food available per capita has been declining *continuously* based on availability of cereal grains during the past 23 years (FAO 1961–2006). Cereal grains make up an alarming 80% of the world's food supply (Pimentel and Pimentel 2008). Although grain yields per hectare in both developed and developing countries are still gradually increasing, the rate of increase is slowing, while the world population and its food needs

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are rising (FAO 1961–2006; PRB 2007). For example, from 1950 to 1980, US grain yields increased at about 3% per year. Since 1980, the annual rate of increase for corn and other grains is only approximately 1% (USDA 1980–2006). Worldwide the rate of increase in grain production is not keeping up with the rapid rate of world population growth of 1.1% (PRB 2007).

The resulting decrease in food supply results in widespread malnutrition. There are more deaths from malnutrition than any other cause of death in the world today (Pimentel *et al.* 2007). The World Health Organization reports more than 3.7 billion people (56% of the global population) are currently malnourished, and that number is steadily increasing. Although much of the land worldwide is occupied by grains and other crops, malnutrition is still globally prevalent.

World Cropland and Water Resources

More than 99.7% of human food comes from the terrestrial environment, while less than 0.3% comes from the oceans and other aquatic ecosystems (FAO 2002). Worldwide, of the total 13 billion hectares of land area, the percentages in use are: cropland, 11%; pasture land, 27%; forest land, 32%; urban, 9%; and other 21%. Most of the remaining land area (21%) is unsuitable for crops, pasture, and/or forests because the soil is too infertile or shallow to support plant growth or the climate and region are too harsh, too cold, dry, steep, stony, or wet (FAOSTAT 2001). Most of the suitable cropland is already is in use.

As the human population continues to increase rapidly, there has been an expansion of diverse human activities that have dramatically reduced cropland and pasture land. Much vital cropland and pastureland has been covered by transportation systems and urbanization. In the USA, about 0.4 ha (one acre) of land per person is covered with urbanization and highways (USCB 2007). In 1960, when the world population numbered only three billion, approximately 0.5 ha was available per person for the production of a diverse, nutritious diet of plant and animal products (Giampietro and Pimentel 1994). It is widely agreed that 0.5 ha is essential for a healthy diet (UN 1999). China's recent explosion in development provides an example of rapid declines in the availability of per capita cropland (Pimentel and Wen 2004). The current available cropland in China is only 0.08 ha per capita. This relatively small amount of cropland provides the people in China with a predominantly vegetarian diet, which requires less energy, land, and biomass than the typical American diet.

In addition to land, water is a vital controlling factor in crop production (Gleick 1996). The production of 9 t/ha of corn requires about seven million liters of water (about 700,000 gallons of water per acre) (Pimentel *et al.* 2004). Other crops also require large amounts of water. Irrigation provides much of the water for world food production. For example, 17% of the crops that are irrigated worldwide provide 40% of the world food supply (FAO 2002). A major concern is that world-wide availability of irrigation water is projected to decline further because of global warming (Cline 2007).

Energy Resources and Use

Since the industrial revolution of the 1850s, the rate of energy use from all sources has been growing even faster than the world population. For example, from 1970 to 1995, energy use increased at a rate of 2.5% per year (doubling every 30 years) compared with the worldwide population growth of 1.7% per year (doubling every 40 to 60 years) (Pimentel and Pimentel 2008). Developed countries annually consume about 70% of the fossil energy worldwide, while the developing nations, which have about 75% of the world population, use only 30% of world fossil energy (International Energy Annual 2006).

Although about 50% of all the solar energy captured worldwide by photosynthesis is used by humans for food, forest products, and other systems, it is still inadequate to meet all human food production needs (Pimentel 2001). To make up for this shortfall, about 473 quads (one quad=1×10^{15} BTU) of fossil energy—mainly oil, gas, coal, and a small amount of nuclear—are utilized worldwide each year (International Energy Annual 2006). Of these 473 quads, about 100 quads (or about 22%) of the world's total energy are utilized just in the United States, which has only 4.5% of the world's population (USCB 2007).

Each year, the USA population uses three times more fossil energy than the total solar energy captured by all harvested US crops, forests, and grasses (Table 1). Industry, transportation, home heating and cooling, and food production account for most of the fossil energy consumed in the United States (USCB 2007). Per capita use of fossil

Table 1 Total amount of above ground biomass except for some crops that include underground biomass and solar energy captured each year in the United States

Crops	901×10^6 tons	14.4×10^{15} BTU
Pasture	600×10^6 tons	9.6×10^{15} BTU
Forest	527×10^6 tons	8.4×10^{15} BTU
Total	$2,028\times10^6$ tons	32.4×10^{15} BTU

An estimated 32×10^{15} BTU of sunlight reaching the USA per year suggests that the green plants in the USA are collecting 0.1% of the solar energy (Jölli and Giljum 2005; Crop Production 2007; Crop Harvest 2007; Forest Service 2007).

energy in the United States per year amounts to about 9,500 l of oil equivalents—more than seven times per capita use in China (Pimentel and Pimentel 2008). In China, most fossil energy is used by industry, although approximately 25%, is now used for agriculture and in the food production system (Pimentel and Wen 2004).

Worldwide, the earth's natural gas supply is considered adequate for about 40 years and that of coal for about 100 years (BP 2005; Youngquist 1997; Lunsford 2007; Konrad 2007; IEA 2007). In the USA, natural gas is already in short supply: it is projected that the USA will deplete its natural gas resources in about 20 years (Youngquist and Duncan 2003). Many agree that the world reached peak oil and natural gas in 2007; from this point, these energy resources are declining slowly and continuously, until they run out altogether (Youngquist and Duncan 2003; Campbell 2006; Heinberg 2007; Lunsford 2007; Konrad 2007; IEA 2007).

Youngquist (1997) reports that earlier estimates of the amount of oil and gas new exploration drilling would provide, were very optimistic as to the amount of these resources to be found in the United States. Both the US oil production rate and existing reserves have continued to decline. Domestic oil and natural gas production has been decreasing for more than 30 years and are projected to continue to decline (USCB 2004–2005, 2007). Approximately 90% of US oil resources have already been exploited (W. Youngquist, petroleum geologist, Eugene, Oregon, 2002, personal communication). At present, the United States is importing more than 63% of its oil (USCB 2007), which puts its economy at risk due to fluctuating oil prices and difficult international political situations, as was seen previously during the 1973 oil crisis, the 1991 Gulf War, and the current Iraq War (Mackay 2002).

Biomass Resources

The total sustainable world biomass energy potential has been estimated to be about 92 quads (10^{15} BTU) per year (Parikka 2004), which represents 19% of total global energy use. The total forest biomass produced worldwide is 38 quads per year (Parikka 2004), which represents 8% of total energy use. In the USA, only 1% to 2% home heating is achieved with wood (USCB 1990).

Global forest area removed each year totals 15 million ha (Forest Degradation Data 2007). Global forest biomass harvested is just over 1,431 billion kg per year, of which 60% is industrial roundwood and 40% is fuelwood (FAOSTAT 2005). About 90% of the fuelwood is utilized in developing countries (Parikka 2004). A significant portion (26%) of all forest wood is converted into charcoal (Arnold and Jongma 2007). Production of charcoal causes between 30% and 50% of the wood energy to be lost (Demirba 2001) and produces large quantities of smoke. On the other hand, charcoal is cleaner burning and thus produces less smoke than burning wood fuel directly (Arnold and Jongma 2007); it is dirty to handle but lightweight.

Worldwide, most biomass is burned for cooking and heating. In developing countries, about 2 kcal of wood are utilized in cooking 1 kcal of food (Fujino *et al.* 1999). Thus, more biomass and more land and water are needed to produce the biofuel for cooking than are needed to produce the food. However, biomass can also be converted into electricity. Assuming that optimal yield globally of three dry metric tons (t/ha) per year of woody biomass can be harvested sustainably (Ferguson 2001, 2003), this would provide a gross energy yield of 13.5 million kcal/ha. Harvesting this wood biomass requires an energy expenditure of approximately 30 l of diesel fuel per hectare, plus the embodied energy for cutting and collecting wood for transport to an electric power plant. Thus, the energy input per output ratio for such a system is calculated to be 1:25 (Hendrickson 1993).

Per capita consumption of woody biomass for heat in the USA amounts to 625 kg per year (Kitani 1999). The diverse biomass resources (wood, crop residues, and dung) used in developing nations averages about 630 kg per capita per year (Kitani 1999).

Woody biomass has the capacity to supply the USA with about five quads (1.5×10^{12} kWh thermal) of its total gross energy supply by the year 2050, provided that the amount of forest-land stays constant (Pimentel 2009). A city of 100,000 people using the biomass from a sustainable forest (3 t/ha per year) for electricity requires approximately 200,000 ha of forest area, based on an average electrical demand of slightly more than one billion kilowatt-hours (electrical energy [*e*]) (860 kcal=1 kWh; Pimentel 2009).

Air quality impacts from burning biomass are less harmful than those associated with coal, but more harmful than those associated with natural gas (Pimentel 2001). Biomass combustion releases more than 200 different chemical pollutants, including 14 carcinogens and four cocarcinogens, into the atmosphere (Burning Issues 2006). As a result, approximately four billion people globally suffer from continuous exposure to smoke (Smith 2006). In the USA, wood smoke kills 30,000 people each year (EPA 2002), although many of the pollutants from electric plants that use wood and other biomass can be mitigated. These controls include the same scrubbers that are frequently installed on coal-fired plants.

An estimated 2.0 billion tons of biomass is produced per year on US land area (Table 1). This translates into about 32 quads of energy, which means that the solar energy captured by all the plants in the USA per year equates to only 32% of the energy currently consumed as fossil energy (Pimentel *et al.* 2008). There is insufficient US biomass for ethanol and biodiesel production to make the USA oil independent.

Of the total world land area in cropland, pasture, and forest, about 38% is cropland and pasture and about 30% is forests (FAOSTAT 2001). Devoting a portion of this cropland and forest land to biofuels will stress both managed ecosystems and will not be sufficient to solve the world fuel problem.

Corn Ethanol

In the United States, ethanol constitutes 99% of all biofuels (Farrell *et al.* 2006). For capital expenditures, new plant construction costs from $1.05 to $3.00 per gallon of ethanol (Shapouri and Gallagher 2005). Fermenting and distilling corn ethanol requires large amounts of water. The corn is finely ground and approximately 15 l of water are added per 2.69 kg of ground corn. After fermentation, to obtain a liter of 95% pure ethanol from the 10% ethanol and 90% water mixture, 1 l of ethanol must be extracted from the approximately 10 l of the ethanol/water mixture. To be mixed with gasoline, the 95% ethanol must be further processed and more water must be removed, requiring additional fossil energy inputs to achieve 99.5% pure ethanol (Tables 2 and 3). Thus, a total of about 12 l of wastewater must be removed per liter of ethanol produced, and this relatively large amount of sewage effluent has to be disposed of at an energy, economic, and environmental costs.

Manufacture of a liter of 99.5% ethanol uses 46% more fossil energy than it produces and costs $1.05 per liter ($3.97 per gallon; Table 3). The corn feedstock alone requires more than 33% of the total energy input. The largest energy inputs in corn-ethanol production are for producing the corn feedstock plus the steam energy and electricity used in the fermentation/distillation process. The total energy input to produce a liter of ethanol is 7,474 kcal (Table 3). However, a liter of ethanol has an energy value of only 5,130 kcal. Based on a net energy loss of 2,344 kcal of ethanol produced, 46% more fossil energy is expended than is produced as ethanol. The total cost, including the energy inputs for the fermentation/distillation process and the apportioned energy costs of the stainless steel tanks and other industrial materials, is $1,045 per 1,000 l of ethanol produced (Table 3).

Subsidies for corn ethanol total more than $6 billion per year (Koplow 2006). This means that the subsidies per liter of ethanol are 60 times greater than the subsidies per liter of gasoline. In 2006, nearly 19 billion liters of ethanol were produced on 20% of US corn acreage (USCB 2007). This

Table 2 Energy inputs and costs of corn production per hectare in the United States

Inputs	Quantity	kcal × 1,000	Costs ($)
Labor	11.4 h[a]	462[b]	300.00[c]
Machinery	55 kg[d]	1,018[e]	310.00[f]
Diesel	88 L[g]	1,003[h]	500.00
Nitrogen	155 kg[k]	2,480[l]	255.00[m]
Phosphorus	79 kg[n]	328[o]	150.00[p]
Potassium	84 kg[q]	274[r]	78.00[s]
Lime	1,120 kg[t]	315[u]	60.00
Seeds	21 kg[v]	520[w]	230.00[x]
Irrigation	8.1 cm[y]	320[z]	350.00[aa]
Herbicides	6.2 kg[bb]	620[ee]	372.00
Insecticides	2.8 kg[cc]	280[ee]	180.00
Electricity	13.2 kWh[dd]	34[ff]	27.00
Transport	204 kg[gg]	169[hh]	180.00
TOTAL		8,228	$2,992.00
Corn yield 9,400 kg/ha[ii]		33,840	Kilocalorie input/output 1:4.11

[a] NASS (2003)
[b] It is assumed that a person works 2,000 h per year and utilizes an average of 8,000 l of oil equivalents per year
[c] It is assumed that labor is paid $26.32 an hour
[d] Pimentel and Pimentel (2008)
[e] Prorated per hectare and 10 year life of the machinery. Tractors weigh from 6 to 7 tons and harvesters 8 to 10 tons, plus plows, sprayers, and other equipment
[f] Estimated
[g] Estimated
[h] Input 11, 400 kcal per liter
[i] Estimated
[j] Input 10,125 kcal per liter
[k] NASS (2003)
[l] Patzek (2004)
[m] Cost $1.65 per kilogram
[n] NASS (2003)
[o] Input 4,154 kcal per kilogram
[p] Cost $1.90 per kiologram
[q] NASS (2003)
[r] Input 3,260 kcal per kilogram
[s] Cost $0.93 per kilogram
[t] Brees (2004)
[u] Input 281 kcal per kilogram
[v] Pimentel and Pimentel (2008)
[w] Pimentel and Pimentel (2008)
[x] USDA (1997a)
[y] USDA (1997b)
[z] Batty and Keller (1980)
[aa] Irrigation for 100 cm of water per hectare costs $1,000 (Larsen *et al.* 2002)
[bb] Larson and Cardwell (1999)
[cc] USDA (2002)
[dd] USDA (1991)
[ee] Input 100,000 kcal per kilogram of herbicide and insecticide
[ff] Input 860 kcal per kilowatt-hour and requires 3 kWh thermal energy to produce 1 kWh electricity
[gg] Goods transported include machinery, fuels, and seeds that were shipped an estimated 1,000 km
[hh] Input 0.83 kcal per kilogram per kilometre transported
[ii] Average. USDA (2006), USCB (2004–2005)

Table 3 Inputs per 1,000 l of 99.5% ethanol produced from corn

Inputs	Quantity	kcal × 1000	Dollars $
Corn grain	2,690 kg[a]	2,355[a]	856.22
Corn transport	2,690 kg[a]	322[b]	21.40[c]
Water	15,000 L[d]	90[e]	21.16[f]
Stainless steel	3 kg[g]	165[h]	10.60[c]
Steel	4 kg[i]	92[h]	10.60[c]
Cement	8 kg[i]	384[h]	10.60[c]
Steam	2,646,000 kcal[j]	2,646[j]	21.16[k]
Electricity	392 kWh[j]	1,011[j]	27.44[l]
95% ethanol to 99.5%	9 kcal/L[m]	9[m]	40.00
Sewage effluent	20 kg BOD[n]	69[g]	6.00
Distribution	331 kcal/L[o]	331	20.00[o]
Total		7,474	$1,045.18

Output: 1 l of ethanol=5,130 kcal (low heating value). The mean yield of 2.5 gallon pure EtOH per bushel has been obtained from the industry-reported ethanol sales minus ethanol imports from Brazil, both multiplied by 0.95 to account for 5% by volume of the no. 14 gasoline denaturant, and the result was divided by the industry-reported bushels of corn inputs to ethanol plants (see http://petroleum.berkeley.edu/patzek/BiofuelQA/Materials/TrueCostofEtOH.pdf; Patzek 2006)

[a] Data from Table 2

[b] Calculated for 144 km roundtrip

[c] Pimentel (2003)

[d] 15 l of water mixed with each kilogram of grain

[e] Pimentel *et al.* (2004)

[f] Pimentel *et al.* (2004)

[g] 4 kWh of energy required to process 1 kg of BOD (Blais *et al.* 1995)

[h] Newton (2001)

[i] Estimated from the industry reported costs of $85 millions per 65 million gallons/year dry grain plant amortized over 30 years. The total amortized cost is $43.6/1,000 L EtOH, of which an estimated $32 go to steel and cement

[j] Illinois Corn (2004). The current estimate is below the average of 40,000 Btu/gallon of denatured ethanol paid to the Public Utilities Commission in South Dakota by ethanol plants in 2005

[k] Calculated based on coal fuel. Below the 1.95 kWh/gallon of denatured EtOH in South Dakota, see footnote j

[l] $.07 per kilowatt-hour (USCB 2004–2005)

[m] 95% ethanol converted to 99.5% ethanol for addition to gasoline (T. Patzek, University of California, Berkeley, 2004, personal communication)

[n] 20 kg of BOD per 1,000 l of ethanol produced (Kuby *et al.* 1984)

[o] DOE (2002)

19 billion liters represents only 1% of total US petroleum use (USCB 2007).

However, even if we completely ignore corn ethanol's negative energy balance and high economic cost, we still find that it is absolutely not feasible to use ethanol as a replacement for US oil. If all 341 billion kilograms of corn produced annually in the USA (USDA 2006) were converted into ethanol at the current rate of 2.69 kg per liter of ethanol, then 129 billion liters of ethanol could be produced. This would provide only 5% of total oil consumption in the USA And of course, in this situation there would be no corn available for livestock, and other needs.

In addition, the environmental impacts of corn ethanol are enormous:

1. Corn production causes more soil erosion than any other crop grown (NAS 2003).
2. Corn production uses more nitrogen fertilizer than any other crop grown and is the prime cause of the dead zone in the Gulf of Mexico (NAS 2003). In 2006, approximately 4.7 million tons of nitrogen was used in US corn production (USDA 2007). Natural gas is required to produce nitrogen fertilizer. The USA now imports more than half of its nitrogen fertilizer (Huang 2004). In addition, about 1.7 million tons of phosphorus was used in the USA (USDA 2007).
3. Corn production uses more insecticides than any other crop grown (McLaughlin and Walsh 1998).
4. Corn production uses more herbicides than any other crop grown (Patzek 2004).
5. More than 1,700 gallons of water are required to produce one gallon of ethanol (Pimentel and Patzek 2008).
6. Enormous quantities of carbon dioxide are produced. This is due to the large quantity of fossil energy used in production, and the immense amounts of carbon dioxide released during fermentation and soil tillage. All this speeds global warming (Socolow *et al.* 2004).
7. Air pollution is a significant problem (Hodge 2003; Jacobson 2007; Pimentel and Patzek 2007). Burning ethanol emits pollutants into air such as peroxyacetyl nitrate (PAN), acetaldhyde, alkylates, and nitrous oxide (Davis and Thomas 2006). These can have significant detrimental human health effects as well as impact other organisms and ecosystems.

In addition to corn ethanol's intensive environmental degradation and inefficient use of food-related resources, the production of corn ethanol also has a great effect on world food prices. For instance, the use of corn for ethanol production has increased the prices of US beef, chicken, pork, eggs, breads, cereals, and milk by 10% to 20% (Brown 2008). Corn prices have more than doubled during the past year.

Grass and Cellulosic Ethanol

Tilman *et al.* (2006) suggest that all 235 million hectares of grassland available in the USA plus crop residues can be converted into cellulosic ethanol. This suggestion causes concerns among scientists. Tilman *et al.* recommend that crop residues, like corn stover, can be harvested and utilized as a fuel source. This would be a disaster for the agricultural ecosystem because crop residues are vital for protecting topsoil. Leaving the soil unprotected would intensify soil erosion by tenfold or more (Rasnake 1999) and may increase soil loss as much as 100-fold (Fryrear and Bilbro 1994).

Furthermore, even a partial removal of the stover can result in increased CO_2 emissions and intensify acidification and eutrophication due to increased runoff (Lal 2004; Kim and Dale 2005). Already, the US crop system is losing soil ten times faster than the sustainable rate (NAS 2003). Soil formation rates at less than 1 t ha^{-1} $year^{-1}$, are extremely slow (NAS 2003; Troeh *et al.* 2004). Increased soil erosion caused by the removal of crop residues for use as biofuels facilitates soil–carbon oxidation and contributes to the greenhouse emissions problem (Lal 2004).

Tilman *et al.* assume about 1,032 l of ethanol can be produced through the conversion of the 4 t ha^{-1} $year^{-1}$ of grasses harvested. However, Pimentel and Patzek (2007) report a negative 68% return in ethanol produced compared with the fossil energy inputs in switchgrass conversion (Tables 4 and 5). Furthermore, converting all 235 million hectares of US grassland into ethanol at the optimistic rate suggested by Tilman *et al.* would still provide only 12% of annual US consumption of oil (USDA 2006; USCB 2007). Verified data, however, confirm that the output in ethanol would require 1.5 l of oil equivalents to produce 1 l of ethanol (Tables 4 and 5).

To achieve the production of this much ethanol, US farmers would have to displace the 100 million cattle, seven million sheep, and four million horses that are now grazing on 324 million hectares of US grassland and rangeland (USDA 2006). Already, overgrazing is a serious problem on US grassland and a similar problem exists worldwide (Brown 2002). Thus, the assessment of the quantity of ethanol that can be produced on US and world grasslands by Tilman *et al.* (2006) appears to be unduly optimistic.

Converting switchgrass into ethanol results in a negative energy return (Table 5). The negative energy return is 68% or a slightly more negative energy return than corn ethanol production (Tables 3 and 5). The cost of producing a liter of ethanol using switchgrass was 93¢ (Table 5).

Table 4 Average inputs and energy inputs per hectare per year for switchgrass production

Input	Quantity	10^3 kcal	Dollars
Labor	5 h[a]	200[b]	$65[c]
Machinery	30 kg[d]	555	50[a]
Diesel	150 L[e]	1,500	75
Nitrogen	80 kg[e]	1,280	45[e]
Seeds	1.6 kg[f]	100[a]	3[f]
Herbicides	3 kg[g]	300[h]	30[a]
Total	10,000 kg yield[i]	3,935	$268[j]
	40 million kcal yield	input/output ratio 1:02[k]	

[a] Estimated
[b] Average person works 2,000 h per year and uses about 8,000 l of oil equivalents. Prorated this works out to be 200,000 kcal
[c] The agricultural labor is paid $13 per hour
[d] The machinery estimate also includes 25% more for repairs
[e] Calculated based on data from Brummer *et al.* (2000)
[f] Data from Samson (1991)
[g] Calculated based on data from Henning (1993)
[h] 100,000 kcal per kilogram of herbicide
[i] Samson *et al.* (2000)
[j] Brummer *et al.* (2000) estimated a cost of about $400/ha for switchgrass production. Thus, the $268 total cost is about 49% lower than what Brummer *et al.* estimates 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 we have added several inputs not included in Samson *et al.* Still the input/output return of 1:11 would be excellent if the sustained yield of 10 t/ha/yr were possible

Table 5 Inputs per 1,000 l of 99.5% ethanol produced from US switchgrass

Inputs	Quantity	kcal × 1,000	Dollars ($)
Switchgrass	5,000 kg[a]	1,968[b]	500
S. Grass transport	5,000 kg[a]	600[b]	30[c]
Water	250,000 L[d]	140[e]	40[f]
Stainless steel	3 kg[g]	165[g]	11[g]
Steel	4 kg[g]	92[g]	11[g]
Cement	8 kg[g]	384[g]	11[g]
Grind switchgrass	5,000 kg	200[h]	16[h]
Sulfuric acid	240 kg[i]	0	168[m]
Steam	8.1 tons[i]	4,404	36
Lignin	1,250 kg[j]	−1,500	−12
Electricity	666 kWh[i]	1,703	46
95% ethanol to 99.5%	9 kcal/L[k]	9	40
Sewage effluent	40 kg BOD[l]	138[n]	12
Distribution	331 kcal/L[o]	331	20
Total		8,634	$929

Output: 1 l of ethanol=5,130 kcal. The ethanol yield here is 200 L/t dry biomass (dbm). Iogen suggests 320 L/t dbm of straw that contains 25% of lignin. This yield is equal to the average yield of ethanol from corn, 317 L/t dbm (2.5 gal/bu). In view of the difficulties with breaking up cellulose fibers and digesting them quickly enough, the Iogen yield seems to be exaggerated, unless significantly more grinding, cell exploding with steam, and hot sulfuric acid are used
[a] Data from Table 4
[b] Calculated for 144 km roundtrip
[c] Pimentel (2003)
[d] 15 l of water mixed with each kilogram of biomass
[e] Pimentel *et al.* (2004)
[f] Pimentel (2003)
[g] Newton (2001)
[h] Calculated based on grinder information (Wood Tub Grinders 2004)
[i] Estimated based on cellulose conversion (Arkenol 2004)
[j] Wood is about 25% lignin and removing most of the water from the lignin by filtering, the moisture level can be reduced to 200% (Crisp 1999)
[k] 95% ethanol converted to 99.5% ethanol for addition to gasoline (T. Patzek, University of California, Berkeley, 2004, personal communication)
[l] 20 kg of BOD per 1,000 l of ethanol produced (Kuby *et al.* 1984)
[m] Sulfuric acid sells for $7 per kilogram
[n] 4 kWh of energy required to process 1 kg of BOD (Blais *et al.* 1995)
[o] DOE (2002)

Several problems exist the conversion of cellulosic biomass into ethanol. First, it takes from two to five times more cellulosic biomass to achieve the same quantity of starches and sugars as are found in the same quantity of corn grain. Thus, two to five times more cellulosic material must be produced and handled compared with corn grain (Pimentel and Patzek 2007). In addition, the starches and sugars are tightly held in lignin in the cellulosic biomass. They can be released using a strong acid to dissolve the lignin. Once the lignin is dissolved, the acid action is stopped with an alkali. Now the solution of lignin, starches, and sugars can be fermented.

Some claim that the lignin can be used as a fuel. Clearly, it cannot when dissolved in water. Usually less than 25% of the lignin can be extracted from the water mixture using various energy intensive technologies (Pimentel and Patzek 2007).

Soybean Biodiesel

Processed vegetable oils from soybean, sunflower, rapeseed, oil palm, and other oil plants can be used as fuel in diesel engines. Unfortunately, producing vegetable oils for use in diesel engines is costly in terms of economics and energy (Ozaktas 2000; Pimentel and Patzek 2007; Tables 6 and 7). A slight net return on energy from soybean oil is possible only if the soybeans are grown without commercial nitrogen fertilizer. The soybean, since it is a legume, will under favorable conditions produce its own nitrogen. Still soy has a 63% net fossil energy loss (Table 7).

The USA provides $500 million in subsidies for the production of 850 million liters of biodiesel (Koplow 2006), which is 74 times greater than the subsidies per liter of diesel fuel. The environmental impacts of producing soybean biodiesel are second only to that of corn ethanol:

1. Soybean production causes significant soil erosion, second only to corn production (NAS 2003).
2. Soybean production uses large quantities of herbicides, second only to corn production (USDA 2006). These herbicides cause major pollution problems with natural biota in the soybean production areas (Artuzi and Contiero 2006; Pimentel 2006).
3. The USDA (2005) reports a soybean yield worldwide to be 2.2 tons per hectare.

With an average oil extraction efficiency of 18% (USDA 1975, 2005), the average oil yield per year would be approximately 0.4 tons per hectare. This converts into 454 l of oil per hectare. Based on current US diesel consumption of 227 billion liters/year (Tickell 2006), this would require more than 500 million hectares of land in soybeans or more than half the total area of the USA planted just for soybeans! All 71 billion tons of soybeans produced in the USA (USDA 2006) could only supply 2.6% of total US oil consumption.

Table 6 Energy inputs and costs in soybean production per hectare in the USA

Inputs	Quantity	kcal × 1,000	Costs ($)
Labor	7.1 h[a]	284[b]	112.00[c]
Machinery	20 kg[d]	360[e]	181.00[f]
Diesel	38.8 L[a]	442[g]	25.00
Gasoline	35.7 L[a]	270[h]	16.00
LP gas	3.3 L[a]	25[i]	1..00
Nitrogen	3.7 kg[j]	59[k]	28.00[l]
Phosphorus	37.8 kg[j]	156[m]	29.00[n]
Potassium	14.8 kg[j]	48[o]	6.00[p]
Limestone	2000 kg[v]	562[d]	56.00[v]
Seeds	69.3 kg[a]	554[q]	59.00[r]
Herbicides	1.3 kg[j]	130[e]	32.00
Electricity	10 kWh[d]	29[s]	1.00
Transport	154 kg[t]	40[u]	56.00
Total		2,959	$602.00
Soybean yield 2,890 kg/ha[w]		10,404	Kilocalorie input/ output 1:3.52

[a] Ali and McBride (1990)
[b] It is assumed that a person works 2,000 h per year and utilizes an average of 8,000 l of oil equivalents per year
[c] It is assumed that labor is paid $13 an hour
[d] Pimentel and Pimentel (2008)
[e] Machinery is prorated per hectare and a 10 year life of the machinery. Tractors weigh from 6 to 7 t and harvesters from 8 to 10 tons, plus plows, sprayers, and other equipment
[f] College of Agri., Consumer & Environ. Sciences (1997)
[g] Input 11,400 kcal per liter
[h] Input 10,125 kcal per liter
[i] Input 7,575 kcal per liter
[j] Economic Research Statistics (1997)
[k] Patzek (2004)
[l] Hinman *et al.* (1992)
[m] Input 4,154 kcal per kilogram
[n] Cost 77¢ per kilogram.
[o] Input 3,260 kcal per kilogram
[p] Costs 41¢ per kilogram
[q] Pimentel *et al.* (2002)
[r] Costs about 85¢ per kilogram
[s] Input 860 kcal per kilowatt-hour and requires 3 kWh thermal energy to produce 1 kWh electricity
[t] Goods transported include machinery, fuels, and seeds that were shipped an estimated 1,000 km
[u] Input 0.83 kcal per kilogram per kilometre transported
[v] Mississippi State University Extension Service (1999)
[w] USDA (2004)

Rapeseed and Canola Biodiesel

The European Biodiesel Board estimates a total biodiesel production of 4.89 million tons for the year 2006 (EBB 2007). Well suited to the colder climates, rapeseed is the

Table 7 Inputs per 1,000 kg of biodiesel oil from soybeans

Inputs	Quantity	kcal × 1,000	Costs ($)
Soybeans	5,556 kg[a]	5,689[a]	1,157.00[a]
Electricity	270 kWh[b]	697[c]	18.90[d]
Steam	1,350,000 kcal[b]	1,350[b]	11.06[e]
Cleanup water	160,000 kcal[b]	160[b]	1.31[e]
Space heat	152,000 kcal[b]	152[b]	1.24[e]
Direct heat	440,000 kcal[b]	440[b]	3.61[e]
Losses	300,000 kcal[b]	300[b]	2.46[e]
Stainless steel	11 kg[f]	605[g]	18.72[h]
Steel	21 kg[f]	483[g]	18.72[h]
Cement	56 kg[f]	2,688[g]	18.72[h]
Total		12,564	$1,251.74

The 1,000 kg of biodiesel produced has an energy value of 9 million kilocalories. In addition, 200 ml (2,080 kcal) of methanol must be added to the soy oil for transesterification. With an energy input requirement of 14.7 million kilocalories, there is a net loss of energy of 63%. If a credit of 7.4 million kilocalories is given for the soy meal produced, then the net loss is less. The cost per kilogram of biodiesel is $1.25

[a] Data from Table 6

[b] Data from Singh (1986)

[c] An estimated 3 kWh thermal is needed to produce a kilowatt-hour of electricity

[d] Cost per kilowatt-hour is 7¢

[e] Calculated cost of producing heat energy using coal

[f] Calculated inputs

[g] Calculated from Newton (2001)

[h] Calculated

dominant crop used in European biodiesel production. Often confused with canola, rapeseed is an inedible crop of the *Brassica* family yielding oil seeds high in erucic acid. Canola is in the same family, but is a hybrid created to lower saturated fat content and erucic acid content for human consumption in cooking oil and margarine (Tickell 2006).

Rapeseed-based biodiesel yields in Europe averaged 1,390 l per hectare in 2005 (Frondel and Peters 2007). Using the density of biodiesel defined as 0.88 kg/l (Frondel and Peters 2007), it can be estimated that the average annual production of rapeseed biodiesel in Europe is 1.1 million tons total. Because of its high oil content (30%), rapeseed is preferred as a biodiesel feedstock source (Tickell 2006). While Europe currently dominates rapeseed production in the world, as the market for high-yield oilseed feedstock for biodiesel grows, interest in canola and rapeseed oil is likely to increase in many northern states of the USA, and Canada (Tickell 2006).

Rapeseed and canola require the application of fertilizers and pesticides in production. The energy required to make these pesticides and fertilizers detracts from the overall net energy produced (Frondel and Peters 2007). Although soybeans contain less oil than canola, about 18% soy oil compared with 30% oil for canola oil, soybeans can be produced with nearly zero nitrogen inputs (Pimentel *et al.* 2008).

The biomass yield of rapeseed/canola per hectare is also lower than that of soybeans—about 1,600 kg/ha for rapeseed/canola compared with 2,890 kg/ha for soybeans (Pimentel *et al.* 2008; USDA 2004). The production of 1,568 kg/ha rapeseed/canola requires an input of about 4.4 million kilocalories per hectare and costs about $669/ha (Pimentel *et al.* 2008). About 3,333 kg of rapeseed/canola oil is required to produce 1,000 kg of biodiesel (Pimentel *et al.* 2008). Therefore, all 333 million tons of rapeseed and canola produced in the USA in 2006 (USDA 2007) could be used to make 100 million liters of biodiesel, or 0.005% of the total oil used in the USA. The total energy input to produce the 1,000 l of rapeseed/canola oil is 13 million kilocalories. This suggests a net loss of 58% of energy inputs (Pimentel *et al.* 2008). The cost per kilogram of biodiesel is also high, at $1.52. Rapeseed and canola are energy intensive and economically inefficient biodiesel crops.

Oil Palm

There is a major effort to plant and harvest oil palms for biofuels in some tropical developing countries, especially Indonesia, Malaysia, Thailand, Colombia, and some in West Africa (Thoenes 2007). In the last 20 years, the production of vegetable oil has more than doubled. Palm oil makes up 23% of biological oils and fats produced worldwide (MPOA 2005). In 2003, more than 123.5 million tons of palm oil were produced worldwide, mostly in Indonesia and Malaysia, the world's leading producers (MPOA 2005).

The oil palm, once established, after 4 years will produce about 4,000 kg of oil per hectare per year (Carter *et al.* 2007). The energy inputs for maintaining the hectare of oil palm are indicated in Pimentel *et al.* (2008). The data suggest that about 7.4 million kilocalories are required to produce 26,000 kg of oil palm bunches. This 26,000 kg is sufficient palm nuts to produce 4,000 kg of palm oil. A total of 6.9 million kilocalories are required to process 6,500 kg of palm nuts to produce 1 ton of palm oil (Pimentel *et al.* 2008). Thus, the net return on fossil energy invested in production and processing totals 30%. This is clearly a better return than corn ethanol and soybean biodiesel. However, an estimated 200 ml (2,080 kcal) of methanol is a required addition to the 1,000 kg of palm oil, for transesterification. This results in a negative 8% net energy output for palm oil.

There are several negative environmental and social issues associated with oil palm plantations. First, the removal of tropical rainforests to plant the oil palm results in an increase in CO_2 (Thoenes 2007). Secondly, the removal of tropical rain forests and the planting of oil palms reduces the biodiversity of the ecosystem. Finally, using oil palm for fuel reduces the availability of palm oil for human use and increases the price of the oil (Thoenes 2007).

Algae for Oil Production

Some cultures of algae consist of 30% to 50% oil (Dimitrov 2007). Thus, there is growing interest using algae to increase US oil supply based on the theoretical claims that 47,000 to 308,000 l ha^{-1} $year^{-1}$ (5,000 to 33,000 gallons/acre) of oil could be produced using algae (Briggs 2004; Vincent Inc. 2007). The calculated cost per barrel would be $15 (Green Car 2006). Currently, oil in the US market is selling for over $50 per barrel. If the above estimated production and price of oil produced from algae were exact, US annual oil needs could theoretically be met if 100% of all US land were in algal culture.

Despite all the algae-related research and claims dating back to 1970s, none of the projected algae and oil yields have been achieved (Dimitrov 2007). To the contrary, one calculated estimate based on all the included costs using algae would be $800 per barrel, not $15 per barrel, as quoted above. Algae, like all plants, require large quantities of nitrogen and water in addition to significant fossil energy inputs for the production system (Goldman and Ryther 1977).

Conclusion

A rapidly growing world population and rising consumption of fossil fuels is increasing demand for both food and biofuels. That will exaggerate both food and fuel shortages. Producing biofuels requires huge amounts of both fossil energy and food resources, which will intensify conflicts among these resources.

Using food crops to produce ethanol raises major nutritional and ethical concerns. Nearly 60% of humans in the world are currently malnourished, so the need for grains and other basic foods is critical (WHO 2005). Growing crops for fuel squanders land, water, and energy resources vital for the production of food for people. Using food and feed crops for ethanol production has brought increases in the prices of US beef, chicken, pork, eggs, breads, cereals, and milk of 10% to 20% (Brown 2008). In addition, Jacques Diouf, Director General of the UN Food and Agriculture Organization reports that using food grains to produce biofuels already is causing food shortages for the poor of the world (Diouf 2007). Growing crops for biofuel not only ignores the need to reduce natural resource consumption, but exacerbates the problem of malnourishment worldwide by turning food grain into biofuel.

Recent policy decisions have mandated increased production of biofuels in the United States and worldwide. For instance, in the Energy Independence and Security Act of 2007, President Bush set "a mandatory renewable fuel standard (RFS) requiring fuel producers to use at least 36 billion gallons of biofuel in 2022." This would require 1.6 billion tons of biomass harvested per year and would require harvesting 80% of all biomass in the USA, including all agricultural crops, grasses, and forests (Table 1). With nearly total biomass harvested, biodiversity and food supplies in the USA would be decimated.

Increased biofuel production also has the capability to impact the quality of food plants in crop systems. The release of large quantities of carbon dioxide associated with the planting and processing of plant materials for biofuels is reported to reduce the nutritional quality of major world foods, including wheat, rice, barley, potatoes, and soybeans (Southwestern University 2008). When crops are grown under high levels of carbon dioxide, protein levels may be reduced as much as 15%.

Many problems associated with biofuels have been ignored by some scientists and policy-makers. The production of biofuels that are being created in order to diminish dependence on fossil fuels, actually depends on fossil fuels. In most cases, more fossil energy is required to produce a unit of biofuel compared with the energy that it produces (Tables 1, 2, 3, 4, 5, 6 and 7). Furthermore, the USA is importing oil and natural gas to produce biofuels, which is making the USA further oil independent. Publications promoting biofuels have used incomplete or insufficient data to support their claims. For instance, claims that cellulosic ethanol provides net energy (Tilman *et al.* 2006) have not been experimentally verified because most of their calculations are *theoretical*. Finally, environmental problems, including water pollution from fertilizers and pesticides, global warming, soil erosion and air pollution are intensifying with biofuel production. There is simply not enough land, water, and energy to produce biofuels.

Most conversions of biomass into ethanol and biodiesel result in a negative energy return based on careful up-to-date analysis of all the fossil energy inputs. Four of the negative energy returns are: corn ethanol at minus 46%; switchgrass at minus 68%; soybean biodiesel at minus 63%; and rapeseed at minus 58%. Even palm oil production in Thailand results in a minus 8% net energy return, when the methanol requirement for transesterification is considered in the equation.

Increased use of biofuels further damages the global environment and especially the world food system.

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