RESEARCH AND ANALYSIS

Cumulative Energy and Global Warming Impact from the Production of Biomass for Biobased Products

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Summary

The cumulative energy and global warming impacts associated with producing corn, soybeans, alfalfa, and switchgrass and transporting these crops to a central crop processing facility (called a "biorefinery") are estimated. The agricultural inputs for each crop are collected from seven states in the United States: Illinois, Indiana, Iowa, Michigan, Minnesota, Ohio, and Wisconsin. The cumulative energy requirement for producing and transporting these crops is 1.99 to 2.66 megajoules/kilogram (MJ/kg) for corn, 1.98 to 2.04 MJ/kg for soybeans, 1.24 MJ/kg for alfalfa, and 0.97 to 1.34 MJ/kg for switchgrass. The global warming impact associated with producing biomass is 246 to 286 grams (g) CO_2 equivalent/kg for corn, 159 to 163 g CO_2 equivalent/kg for soybeans, 89 g CO_2 equivalent/kg for alfalfa, and 124 to 147 g CO_2 equivalent/kg for switchgrass. The detailed agricultural data are used to assess previous controversies over the energy balance of bioethanol and, in light of the ongoing debates on this topic, provide a needed foundation for future life-cycle assessments.

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Introduction

Interest in biobased products has gradually increased because of energy security concerns; the continuing decline in rural economies; environmental impacts of reliance on fossil carbon for fuels, chemicals, and materials; and the increasingly competitive economics of biobased products. Biobased products are energy products or organic materials derived from plant biomass, for example, ethanol from corn or other crops,[1] biodiesel from soybeans, and plastics from sugars[2] (NRC 2000). Around 57% of total oil demand in the United States in 2000 was imported from foreign countries (U.S. DOE 2001). Biobased products, particularly fuels, can potentially reduce the amount of petroleum imported.

This is the first in a series of articles dealing with the likely environmental characteristics of biobased products in a life-cycle context. Here we focus on the cumulative energy and global warming impact associated with producing selected crops and transporting them to the biorefinery. The choice of crops is justified below. Subsequent articles will focus on (1) how agricultural production practices for these crops can influence important environmental parameters, (2) environmental impacts of the biorefineries that convert plant material to biobased products, (3) environmental consequences of using these products, particularly in comparison with the petroleum-derived products that they are likely to replace, and (4) system-level studies of integrated crop production and biorefinery systems.

The important effect that agricultural production practices can have on environmental parameters of biobased products is well illustrated by the case of ethanol produced from corn grain. Early studies found that corn ethanol produces negative net energy (i.e., there is less energy in the ethanol than the energy required to produce the ethanol). These widely cited negative findings naturally influenced the public debate over the desirability of corn ethanol as a fuel. Using more recent agricultural production data that are also more specific to the large corn-producing states of the United States, we find that corn ethanol has positive net energy. The controversy over corn ethanol net energy and greenhouse gas production has made clear that these measures are highly sensitive to agricultural production data and that a careful and thorough accounting of the biomass crop production system is needed.

Overview of the Crop Production and Biorefinery System

Corn, soybeans, and alfalfa are major agricultural products in the United States and other countries, with nearly 200 million total acres[3] grown (including all three crops) in the United States. The four crops under consideration in this article represent well the range of production practices and inputs for crops produced in North America today that might serve as feedstocks for biobased products. They represent (1) an annual grain row crop (corn) that produces large amounts of residue (corn stover), (2) an annual leguminous oilseed row crop (soybeans), (3) a widely grown perennial legume field crop (alfalfa), and (4) a potential new perennial nonleguminous field crop (switchgrass). In fact, corn and soybeans are already used to produce industrial products including fuels, materials, and lubricants. The biorefining technologies for corn and soybeans are relatively well established, although improvements continue to occur in biorefining procedures (Shapouri et al. 2002).[4] Alfalfa and switchgrass (and corn stover) are lignocellulosic materials for which biorefining technologies are not well established (Wyman 1999).

For corn and soybeans, the grain and seed, respectively, are the harvested, transported, and biorefined portions of the plant. In alfalfa and switchgrass, however, the entire above-ground portion of the plant is assumed to be harvested (using similar equipment), transported, and biorefined (McLaughlin et al. 2002). Conventional, existing crop harvesting and transportation practices are assumed in this article. We do not make comparisons between crops at this point. Meaningful comparisons can only be done when the biorefining system and product use phase are included in the analysis, and that is beyond the scope of this article.

In the biorefinery, crops are processed into a wide variety of industrial products (NRC 2000).

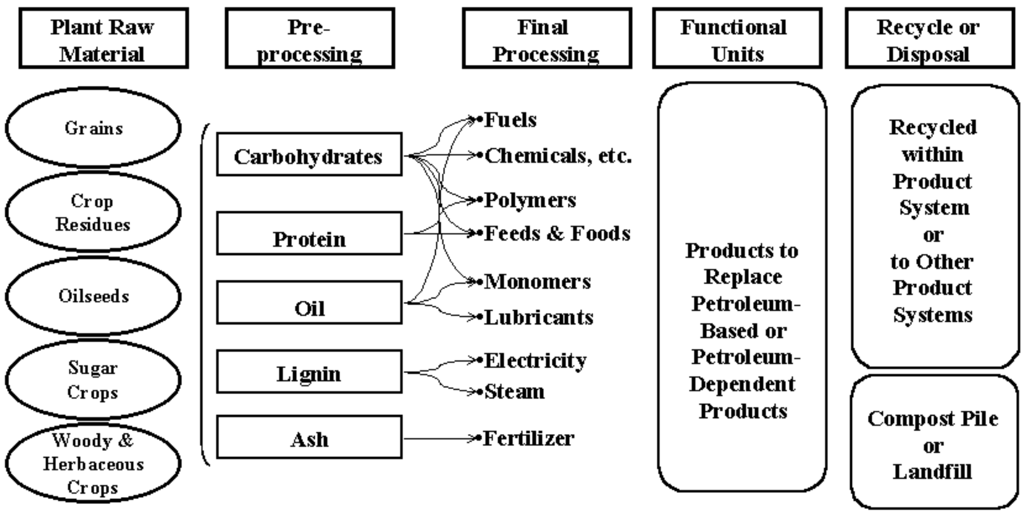

Figure 1 Overall system definition for production and use of biobased products.

Figure 1 outlines how various crops might be processed to a smaller number of intermediate compounds in the biorefinery (carbohydrates, proteins, oils, etc.), and then these intermediate compounds might be upgraded by further processing to a wide variety of industrial products. The biorefining system and the subsequent use of these biobased products generate their own sets of environmental impacts. Therefore, evaluating the environmental aspects of biobased products should consider all of the phases of the biobased product life cycle, agricultural production, biorefining, product use, and waste management as an integrated whole, employing life-cycle assessment (LCA) according to strict international standards to identify the likely environmental impacts of producing and using biobased products.

Several articles with a life-cycle orientation have already been published regarding the environmental performance of biobased products. Shapouri and colleagues (1995, 2002) estimated the net energy balance of ethanol delivered from corn grain. They found wide variations in the net energy value estimates from several studies due to differences in corn yields, ethanol conversion technologies, fertilizer manufacturing efficiency, fertilizer application rates, by-product evaluation, and the number of energy inputs. They concluded that the energy in a gallon[5] of fuel ethanol was higher than the energy required to produce a gallon of ethanol. Wang and colleagues (1999) also concluded that the use of ethanol from corn in the transportation sector could reduce greenhouse gases as well as fossil energy use.

In contrast, Pimentel (1991, 2002) found that the energy requirement for producing ethanol derived from corn grain was higher than the energy content of ethanol. Ulgiati (2001) concluded that the bioethanol fuel option on a large scale was not a viable alternative based on economic and energy analyses of his case study data and he calculated possible improvements in yield and efficiency.

The first three studies (Shapouri et al. 1995, 2002; Wang et al. 1999) showed that using ethanol as a vehicle fuel can save petroleum fuel, especially gasoline, but the last three studies (Pimentel 1991, 2002; Ulgiati 2001) did not. This disagreement is one of the motivations for the detailed and specific attention to data and modeling assumptions in this article. This disagreement is attributable to differing data sets (including data sources and ages) and methodologies. Methodological differences include choices of the system boundaries and the allocation procedures, which must accommodate a multi-input process and an open-loop recycling system.

Sheehan and colleagues (1998) performed a life-cycle inventory of biodiesel and petroleum diesel and concluded that biodiesel from soybeans could reduce consumption of petroleum and would also reduce carbon dioxide, carbon monoxide, particulate matter, and sulfur oxides emissions. On the other hand, biodiesel use increased emissions of nitrogen oxides and hydrocarbon. Gerngross (1999) estimated the fossil fuel equivalent for producing polyhydroxyalkanoates (PHAs) from corn and polystyrene from petroleum, respectively. He found that the fossil fuel equivalent of PHA was slightly larger than that of polystyrene. Kurdikar and colleagues (2001) pointed out that plant-based PHA resin produced using fossil fuel sources had no greenhouse gas advantage over polyethylene resin. They also found that using biomass energy from corn stover in the PHA system, instead of fossil fuel energy, would result in a better greenhouse gas profile for PHA resin than for polyethylene resin.

These studies (Shapouri et al. 1995, 2002; Wang et al. 1999; Pimentel 1991, 2002; Sheehan et al. 1998; Gerngross 1999) show that the agricultural production processes account for 27% to 44% of the total energy consumption in producing biobased products. As a first step in a comprehensive LCA study of biobased product systems, we have collected agricultural inputs from seven states in the United States: Illinois, Indiana, Iowa, Michigan, Minnesota, Ohio, and Wisconsin. These states are responsible for the majority of the corn, soybeans, and alfalfa grown in the United States. The cumulative energy and the global warming impact associated with the agricultural production practices for corn, soybeans, alfalfa, and switchgrass are estimated and presented as weighted average values.

Methods of Analysis

Cumulative Energy

The cumulative energy includes the energy requirement for producing fuel and the energy delivered by fuel. For example, generating 1 MJ of electricity[6] in the United States requires 2.7 MJ of energy from coal, fossil fuel, natural gas, and nuclear sources. The cumulative energy of electricity can be estimated from equation (1),

$$\begin{aligned} E_{\text{electricity}} = {} & \mathrm{G}_{\text{coal}} \cdot \frac{E_{\text{coal}}}{e_{\text{coal}}} \\ & + \mathrm{G}_{\text{natural gas}} \cdot \frac{E_{\text{natural gas}}}{e_{\text{natural gas}}} \\ & + \mathrm{G}_{\text{nuclear}} \cdot \frac{E_{\text{nuclear}}}{e_{\text{nuclear}}} \\ & + \mathrm{G}_{\text{fuel oil}} \cdot \frac{E_{\text{fuel oil}}}{e_{\text{fuel oil}}} \end{aligned} \tag{1}$$

where E_i is the cumulative energy of the *i*th energy source (MJ/MJ energy delivered), G_j is the fraction of electricity in the power grid from the *j*th fuel type (i.e., coal, natural gas, etc.), and e_j is the electricity generation efficiency.

In equation (1), the hydropower and other power sources are ignored because the cumulative energy of hydropower is assumed to be zero and the portion of other power sources in the electricity power grid is very small in the United States. The cumulative energy of other fuels can be calculated as in equation (2),

$$E_i = \sum_j a_{ij} \cdot E_j + 1 \tag{2}$$

where a_{ij} is the amount of *j*th fuel used in *i*th fuel cycle[7] (MJ/MJ).

The final (unity) term on the right-hand side of equation (2) represents the energy delivered by the fuel itself. A series of linear equations can be easily solved once all parameters are known. The electricity power grid is obtained from Egrid (U.S. EPA 2001), and other parameters are obtained from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model, version 1.5a (Wang 2000). The results are shown in figure 2. The values are estimated based on the higher heating value (HHV)[8] because the energy in the steam produced by fuel combustion is generally recovered in power generating systems. The cumulative energy of electricity in Illinois is highest among all states studied because about 40% of Illinois electricity is generated by nuclear power plants and the upstream processes of nuclear fuel production are more energy intensive than for other fuels. The cumulative energy of nuclear fuel is 1.13 MJ/MJ nuclear fuel, indicating that the energy requirement in uranium mining, transportation, and enrichment is 0.13 MJ/MJ nuclear fuel. A

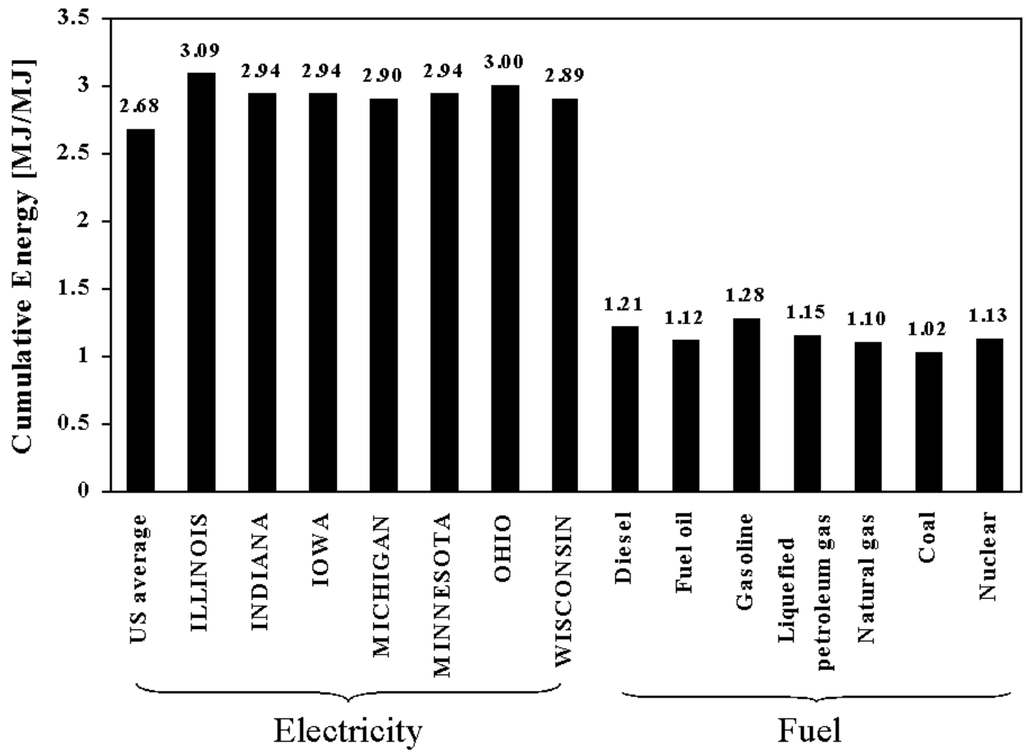

Figure 2 Cumulative energy for electricity and fuel in 2000 (based on HHV).

megajoule of nuclear fuel is that amount of fissile material that would release 1 MJ of total energy during fission.

The energy requirement for producing fertilizers and agrochemicals is estimated from literature values (Shapouri et al. 1995; Wang et al. 1999; Wang 2000; Helsel 1992). The cumulative energy of fertilizers and agrochemicals is shown in table 1.

Table 1 contains two cumulative energy values for nitrogen fertilizer production:[9] One is for the case in which carbon dioxide produced in the ammonia plant is regarded as an emission (i.e., a *waste*), denoted by "nitrogen fertilizer B"; the other value, denoted by "nitrogen fertilizer A," is the result considering the carbon dioxide generated in the ammonia plant as a coproduct. Nitrogen fertilizer in both cases is assumed to consist of ammonia (69%) and urea (31%). We exclude other forms of nitrogen fertilizer (e.g., ammonium nitrate, nitrogen solution, etc.) because these other nitrogen fertilizers are little used in the United States (IFA 2001).

When natural gas is reformed during the manufacture of ammonia, 1,179 kg of carbon dioxide is produced for every 1,000 kg of ammonia. The carbon dioxide is separated using an absorption process and is often captured and utilized in various applications, such as tertiary oil recovery and the production of urea fertilizer. When carbon dioxide is considered a coproduct in ammonia manufacture, the life-cycle flows of the process must be allocated between the two coproducts. In this case, allocation is done using the subdivision allocation approach[10] (Kim and Overcash 2000a). The cumulative energy of nitrogen fertilizer A that results is slightly less than half the cumulative energy of nitrogen fertilizer B due to the allocation of the process energy to both ammonia and carbon dioxide in the ammonia plant. The process energy for the ammonia plant is from the work of Kim and Overcash (2000a), and the energy used in urea production is estimated using chemical process design calculation methods (Jiménez-González et al. 2000; Kim and Overcash 2000b).

Table 1 Cumulative energy of fertilizers and agrochemicals

	Year	*Unit*	*Cumulative energy*
Nitrogen fertilizer (A)	2000[d]	MJ/kg N	32.08
Nitrogen fertilizer (B)	1995,[a] 1997,[b] 2000[c]	MJ/kg N	70.62
Phosphorus fertilizer	1995,[a] 1997,[b] 2000[c]	MJ/kg P_2O_5	19.01
Potassium fertilizer	1995,[a] 1997,[b] 2000[c]	MJ/kg K_2O	9.04
Lime	1995[a]	MJ/kg	1.47
Herbicides	1992[e]	MJ/kg	429.27
Pesticides	1992[e]	MJ/kg	439.73
Boron	2000[f]	MJ/kg	4.65

[a] Shapouri et al. (1995).

[b] Wang et al. (1999).

[c] Wang (2000).

[d] Kim and Overcash (2000a, 2000b).

[e] Helsel (1992).

[f] Jiménez-González et al. (2000).

The cumulative energy for transporting biomass to a biorefinery and for transporting agrochemicals to the field is adapted from GREET 1.5a (Wang 2000). The energy requirement for transporting alfalfa to the biorefinery is assumed to be the same as that of switchgrass, in which 0.2 MJ of diesel is required to haul 1 kg of switchgrass[11] to the biorefinery (about 81 km)[12] because alfalfa and switchgrass have approximately the same energy density. The energy requirement for transporting agrochemicals (including fertilizers, herbicides, and pesticides) is 0.17 MJ of fuel oil and 0.55 MJ of diesel per kilogram. The energy requirement for transportation of corn from farm to biorefinery is 0.15 MJ of diesel per kilogram of corn for a 161 km round trip. Soybeans are assumed to travel the same distance as corn (Wang 2000).

Global Warming Impact

Greenhouse gases (carbon dioxide, methane, and nitrous oxide) are included in estimating the global warming impact. The emission factors for each chemical and energy source are estimated from GREET 1.5a (Wang 2000). Table 2 presents the global impact associated with energy use and chemicals.

Nitrous oxide (N_2O) emissions from synthetic fertilizer application and soil are included in estimating the global warming impact associated with agricultural practices. Wang (2000) assumed that 1.5% of the nitrogen in the nitrogen fertilizer for corn and 1.3% of that for soybeans and switchgrass is converted into nitrous oxide emissions. Wang's value is used as a base-case number here. The U.S. Environmental Protection Agency published a method for estimating nitrous oxide emissions from soil that includes emissions from nitrogen fertilizer, from the decomposition of crop residues, and from nitrogen fixed by nitrogen-fixing crops (U.S. EPA 1999). Nitrous oxide emissions due to the decomposition of crop residues and of fixed nitrogen are not included in this study because the decomposition of crop residues and from nitrogen fixed by biomass depends on subsequent crop systems. Cropping systems are beyond the scope of this study but will be dealt with in future studies.

Carbon dioxide taken up by biomass is eventually released into the air so that net carbon dioxide production approaches zero. Thus, carbon dioxide taken up by biomass is not accounted for in this study. We note, however, that some biobased products, notably solid building and construction materials, can have very long lifetimes and effectively sequester carbon dioxide over their product lifetime. In addition, deep-rooted perennials (such as alfalfa and switchgrass) can also sequester atmospheric carbon in the root zone over very long timescales (McLaughlin and Walsh 1998). We also do not account for changes in soil organic carbon levels due to crop cultivation practices. The dynamics

Table 2 Global warming impact associated with energy use and chemicals

	Unit	Global warming impact
Electricity		
Illinois	g CO_2 equivalent/MJ	1.99E+02
Indiana	g CO_2 equivalent/MJ	3.01E+02
Iowa	g CO_2 equivalent/MJ	2.74E+02
Michigan	g CO_2 equivalent/MJ	2.50E+02
Minnesota	g CO_2 equivalent/MJ	2.28E+02
Ohio	g CO_2 equivalent/MJ	2.77E+02
Wisconsin	g CO_2 equivalent/MJ	2.46E+02
Fuel		
Diesel	g CO_2 equivalent/MJ	1.03E+02
Gasoline	g CO_2 equivalent/MJ	8.80E+01
Liquefied petroleum gas	g CO_2 equivalent/MJ	7.90E+01
Natural gas	g CO_2 equivalent/MJ	6.82E+01
Fuel oil	g CO_2 equivalent/MJ	8.47E+01
Chemicals		
Nitrogen fertilizer (A)	g CO_2 equivalent/kg N	9.72E+02
Nitrogen fertilizer (B)	g CO_2 equivalent/kg N	3.27E+03
Phosphorus fertilizer	g CO_2 equivalent/kg P_2O_5	1.34E+03
Potassium fertilizer	g CO_2 equivalent/kg K_2O	6.42E+02
Lime	g CO_2 equivalent/kg	4.21E+01
Herbicides	g CO_2 equivalent/kg	2.28E+04
Pesticides	g CO_2 equivalent/kg	2.45E+04
Boron	g CO_2 equivalent/kg	3.35E+02

of soil organic carbon depend on a variety of factors beyond the scope of this study, including local climatic conditions, soil texture, and cultivation practices.

Results

Agricultural Processes

The application rates of fertilizers and agrochemicals and the associated corn and soybean yields are collected from the U.S. Department of Agriculture statistics (USDA 2001). Agricultural energy use for corn and soybean production is adapted from the literature (Shapouri et al. 1995; Sheehan et al. 1998). Fertilizer and agrochemical application rates and the yield and energy use in switchgrass production are adapted from a report published by Oak Ridge National Laboratory (Ugarte et al. 2000). For alfalfa, yield is available from the U.S. Department of Agriculture statistics (USDA 2001), and fertilizer application rates are estimated from crop production budgets for each state. For alfalfa production in Indiana, Minnesota, and Wisconsin, average values from other states are used because there are no fertilizer application rate data available for these three states. The amounts of energy required to produce alfalfa and switchgrass are estimated in the same way. The energy consumed in producing switchgrass is based on energy consumption in agricultural machinery fueled by petroleum (e.g., field mowers, balers, and rakes). We assume that the identical machinery is used to produce alfalfa; both alfalfa and switchgrass are forage crops that can be cut, windrowed, baled, and transported with essentially identical machinery (McLaughlin et al. 2002). No energy is required for drying biomass, because the biomass is dried by sunlight in the field. This is the common harvesting practice for all forage crops in the United States, including alfalfa and switchgrass. Tables 3 through 6, which are based on fresh weight, illustrate the fertilizer application rates and the agricultural energy used in biomass production in the seven states.

Nitrogen fertilizer is the primary fertilizer applied to corn. Soybean and alfalfa production requires more phosphorus fertilizer than other fertilizers. Potassium fertilizer is the major mineral requirement for producing alfalfa (alfalfa does not require nitrogen fertilizer because it is a legume, or nitrogen fixer). Although soybeans also fix nitrogen, the U.S. Department of Agriculture statistics (USDA 2001) show that a certain amount of the nitrogen fertilizer is applied in soybean fields. The energy use per kilogram of biomass produced in soybeans is much higher than for the other crops analyzed because of lower soybean yields.

Cumulative Energy Analysis

Figure 3 illustrates the cumulative energy for producing 1 kg of each biomass crop. "A" represents the case for nitrogen fertilizer A (referred to as "case A"), and "B" is the case for cumulative energy estimated using nitrogen fertilizer B, in which carbon dioxide is regarded as a waste (referred to as "case B").

We follow Shapouri and colleagues (1995) and Sheehan and colleagues (1998), who assumed that the energy requirement to grow 1 kg of seed was equal to 150% of the energy required to grow 1 kg of corn and soybeans. The amount of electricity used includes an 8% distribution loss (Wang 2000). The effects of crop rotations including legumes and of carbon dioxide fixation in the plants are both excluded because at this stage of analysis our objective is to present raw data for producing a single biomass crop.

The total cumulative energy for producing 1 kg of corn is 1.99 MJ in case A and 2.66 MJ in case B. The nitrogen fertilizer required is the primary factor in the cumulative energy requirement for producing corn in both cases. Diesel use is the next most important factor. The energy impact associated with transporting corn to the biorefinery is less than 10% of the total in both cases (6.9% to 9.2%). About half the cumulative energy requirement is from the energy associated with fertilizers and agrochemicals used in producing corn. The cumulative energy requirement for producing 1 kg of soybeans is 1.98 MJ in case A and 2.04 MJ in case B. The primary factor in the cumulative energy requirement for producing soybeans is diesel use in both cases because of the low application rate of nitrogen fertilizer. The second most important contributor to the cumulative energy for producing soybeans is gasoline use. Hence, over 65% of the cumulative energy is associated with the liquid fuels used for producing and transporting soybeans.

The cumulative energy requirement for producing 1 kg of alfalfa is 1.24 MJ/kg in both cases, and there is no difference between the two cases because no nitrogen fertilizer is required in producing alfalfa. The primary factor in the cumulative energy requirement for producing alfalfa is diesel use. The energy associated with transporting alfalfa to the biorefinery also contributes significantly to the cumulative energy requirement, as does herbicide use. The cumulative energy requirement for producing 1 kg of switchgrass is 0.97 MJ in case A and 1.34 MJ in case B. Diesel use is the primary factor in the cumulative energy for producing switchgrass in case A, but nitrogen fertilizer is the primary factor in case B. The energy associated with transporting switchgrass to the biorefinery contributes about 20% of the cumulative energy requirement in both cases.

The relative contributions of each energy source are illustrated in figure 4. The primary energy source consumed in producing biomass in case A is diesel, which includes direct use in the field, use in transportation, and also use in the upstream processes of fertilizer and agrochemical production. The primary energy source used for most of the crops in case B is also diesel, but for corn it is natural gas because of the nitrogen fertilizer consumed. The use of diesel in the field is 45% to 76% of the total diesel use in both cases. In the case of natural gas, the major energy consuming activities are the upstream processes, especially nitrogen fertilizer production, which uses natural gas both as a raw material and as a source of process energy.

Global Warming Impact

Figure 5 shows the global warming impact associated with producing 1 kg of biomass. The carbon credit for carbon in crops is not included in

Table 3 Agricultural inputs for corn in 2000

State	*Yield (kg/ha)*	*N (kg/kg corn)*	*P_2O_5 (kg/kg corn)*	*K_2O (kg/kg corn)*	*Herbicides (kg/kg corn)*	*Pesticides (kg/kg corn)*	*Lime (kg/kg corn)*	*Diesel (MJ/kg corn)*	*Gasoline (MJ/kg corn)*	*Liquid propane gas (MJ/kg corn)*	*Electricity (MJ/kg corn)*	*Natural gas (MJ/kg corn)*
Illinois	9.49E+03	1.93E−02	7.93E−03	1.10E−02	3.02E−04	3.36E−05	5.69E−02	2.43E−01	1.63E−01	5.94E−02	1.45E−02	5.81E−02
Indiana	9.24E+03	1.90E−02	8.03E−03	1.37E−02	3.39E−04	1.75E−05	4.14E−02	2.92E−01	1.74E−01	6.34E−02	3.61E−02	5.21E−02
Iowa	9.11E+03	1.58E−02	5.17E−03	6.49E−03	2.52E−04	6.53E−06	3.45E−02	2.32E−01	1.20E−01	1.46E−01	5.94E−03	6.16E−02
Michigan	7.79E+03	1.76E−02	7.10E−03	1.13E−02	4.15E−04	9.60E−06	9.81E−02	4.07E−01	1.42E−01	1.04E−01	1.55E−02	8.92E−02
Minnesota	9.11E+03	1.47E−02	7.56E−03	7.07E−03	1.98E−04	6.90E−06	4.94E−03	2.91E−01	1.31E−01	1.28E−01	3.64E−02	5.56E−02
Ohio	9.24E+03	2.11E−02	8.27E−03	1.06E−02	3.81E−04	2.22E−05	1.70E−02	2.82E−01	1.30E−01	1.27E−01	1.29E−02	3.57E−02
Wisconsin	8.29E+03	1.48E−02	5.95E−03	7.94E−03	3.16E−04	1.80E−05	1.63E−02	5.58E−01	1.37E−01	6.68E−02	9.36E−02	4.44E−02
Average	**9.12E+03**	**1.74E−02**	**7.00E−03**	**9.31E−03**	**2.89E−04**	**1.72E−05**	**3.69E−02**	**2.81E−01**	**1.43E−01**	**1.02E−01**	**2.28E−02**	**5.66E−02**

Note: The corn production of these seven states accounts for 63% of the total U.S. corn production.

Table 4 Agricultural inputs for soybeans in 2000

State	*Yield (kg/ha)*	*N (kg/kg soybeans)*	*P_2O_5 (kg/kg soybeans)*	*K_2O (kg/kg soybeans)*	*Herbicides (kg/ kg soybeans)*	*Pesticides (kg/kg soybeans)*	*Diesel (MJ/kg soybeans)*	*Gasoline (MJ/kg soybeans)*	*Liquid propane gas (MJ/kg soybeans)*	*Electricity (MJ/kg soybeans)*
Illinois	2.96E+03	6.23E−04	2.87E−03	1.06E−02	3.92E−04	1.11E−07	5.58E−01	3.10E−01	2.91E−02	0.00E+00
Indiana	3.10E+03	7.24E−04	3.55E−03	1.37E−02	3.56E−04	0.00E+00	6.16E−01	3.29E−01	8.14E−04	1.69E−03
Iowa	2.89E+03	3.01E−03	4.09E−03	5.13E−03	4.85E−04	0.00E+00	7.03E−01	3.32E−01	0.00E+00	0.00E+00
Michigan	2.42E+03	2.54E−03	1.02E−02	3.00E−02	4.79E−04	0.00E+00	7.59E−01	3.79E−01	6.57E−03	1.14E−03
Minnesota	2.76E+03	5.99E−04	1.42E−03	6.97E−03	4.20E−04	0.00E+00	1.16E+00	4.83E−01	0.00E+00	9.92E−04
Ohio	2.83E+03	2.00E−03	6.48E−03	1.78E−02	4.23E−04	1.85E−07	7.65E−01	4.47E−01	2.72E−03	3.02E−03
Wisconsin	2.69E+03	1.92E−03	4.90E−03	1.36E−02	3.45E−04	0.00E+00	7.59E−01	3.79E−01	6.57E−03	1.14E−03
Average	**2.88E+03**	**1.51E−03**	**3.79E−03**	**1.07E−02**	**4.21E−04**	**4.78E−08**	**7.39E−01**	**3.66E−01**	**8.37E−03**	**8.05E−04**

Note: The soybean production of these seven states accounts for 65% of the total U.S. soybean production.

Table 5 Agricultural inputs for alfalfa in 2000

State	*Yield* (*kg/ha*)	P_2O_5 (*kg/kg alfalfa*)	K_2O (*kg/kg alfalfa*)	*Herbicide* (*kg/kg alfalfa*)	*Pesticides* (*kg/kg alfalfa*)	*Lime* (*kg/kg alfalfa*)	*Boron* (*kg/kg alfalfa*)	*Diesel* (*MJ/kg alfalfa*)	*Fuel oil* (*MJ/kg alfalfa*)
Illinois	8.52E+03	7.63E−03	1.53E−02	1.63E−04	8.41E−06	2.47E−02	0.00E+00	2.69E−01	4.12E−03
Indiana	9.19E+03	6.23E−03	1.82E−02	3.07E−04	8.70E−06	2.29E−02	9.89E−05	2.63E−01	3.76E−03
Iowa	8.74E+03	6.09E−03	2.24E−02	3.23E−04	9.14E−06	2.40E−02	8.01E−05	2.67E−01	3.93E−03
Michigan	8.29E+03	6.15E−03	2.43E−02	1.63E−04	1.16E−05	2.53E−02	8.43E−05	2.71E−01	3.06E−03
Minnesota	8.07E+03	7.09E−03	2.08E−02	3.50E−04	9.91E−06	2.60E−02	1.04E−04	2.74E−01	3.25E−03
Ohio	8.97E+03	6.67E−03	1.59E−02	6.39E−04	7.99E−06	2.34E−02	9.33E−05	2.65E−01	3.42E−03
Wisconsin	6.73E+03	8.51E−03	2.49E−02	4.20E−04	1.19E−05	3.13E−02	1.25E−04	2.92E−01	3.87E−03
Average	**8.95E+03**	**6.67E−03**	**1.60E−02**	**6.33E−04**	**8.03E−06**	**2.35E−02**	**9.33E−05**	**2.65E−01**	**3.43E−03**

Note: The alfalfa production of these seven states accounts for 32% of the total U.S. alfalfa production.

Table 6 Agricultural inputs for switchgrass in 2000

State	*Yield* (*kg/ha*)	*N* (*kg/kg switchgrass*)	P_2O_5 (*kg/kg switchgrass*)	K_2O (*kg/kg switchgrass*)	*Herbicide* (*kg/kg switchgrass*)	*Lime* (*kg/kg switchgrass*)	*Diesel* (*MJ/kg switchgrass*)	*Fuel oil* (*MJ/kg switchgrass*)
Illinois	1.33E+04	9.67E−03	1.26E−04	6.31E−04	4.20E−05	8.41E−03	2.45E−01	2.89E−03
Indiana	1.28E+04	9.67E−03	1.31E−04	6.57E−04	4.38E−05	8.76E−03	2.46E−01	2.90E−03
Iowa	1.28E+04	9.67E−03	1.31E−04	6.56E−04	4.38E−05	8.75E−03	2.46E−01	2.90E−03
Michigan	7.73E+03	9.67E−03	2.18E−04	1.09E−03	7.26E−05	1.45E−02	2.78E−01	3.26E−03
Minnesota	8.28E+03	9.67E−03	2.03E−04	0.00E+00	6.78E−05	1.36E−02	2.72E−01	3.19E−03
Ohio	1.06E+04	9.67E−03	1.58E−04	7.92E−04	5.28E−05	1.06E−02	2.54E−01	3.00E−03
Wisconsin	8.52E+03	9.67E−03	1.97E−04	9.87E−04	6.58E−05	1.32E−02	2.70E−01	3.17E−03
Average	**1.06E+04**	**9.67E−03**	**1.67E−04**	**6.87E−04**	**5.55E−05**	**1.11E−02**	**2.59E−01**	**3.05E−03**

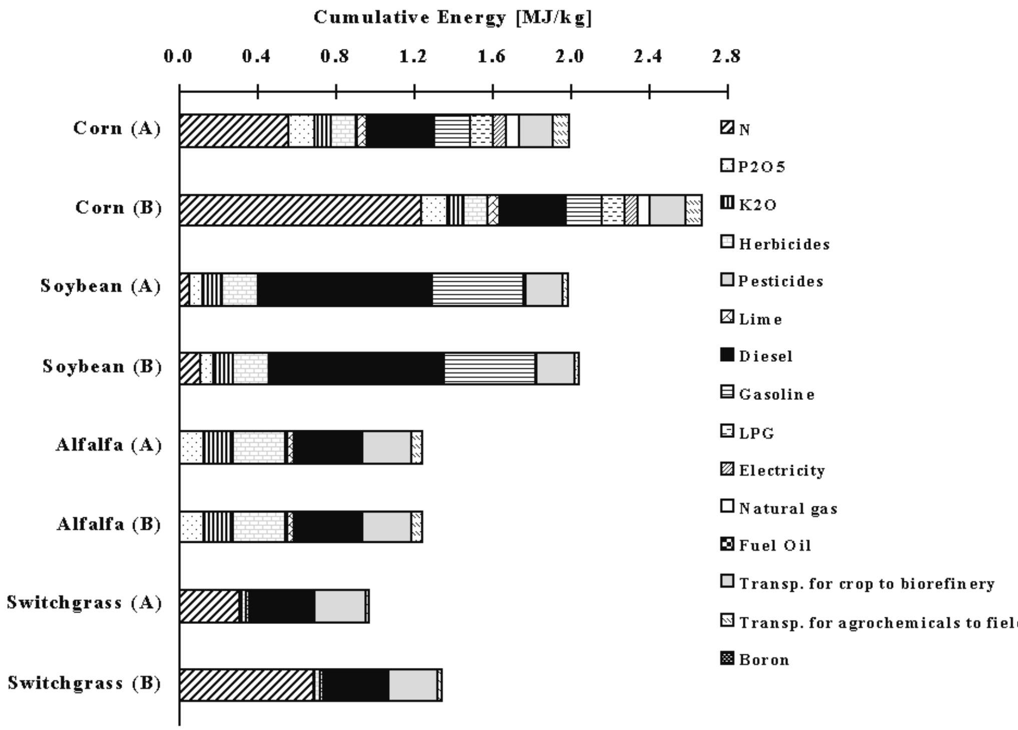

Figure 3 Cumulative energy by input for producing biomass in 2000 disaggregated by input or process. "A" indicates carbon dioxide is a by-product of ammonia manufacture, and "B" indicates carbon dioxide is a waste in the ammonia production process. See text for details. LPG = liquefied petroleum gas.

figure 5. Until we perform a whole system analysis, it is impossible to determine the net carbon uptake by the overall crop production and biorefinery system. For example, the amount of biomass carbon released during bioprocessing depends on the processing method (e.g., by fermentation of sugars to ethanol), and different tillage practices generate different field-level emissions of greenhouse gases.

The global warming impact associated with producing 1 kg of corn is 246 g CO_2 equivalent/kg in case A and 286 g CO_2 equivalent/kg in case B. The primary source of greenhouse gases in both cases is field emissions of nitrous oxide due to nitrogen fertilizer use. The second largest source of greenhouse gases is diesel use in case A and nitrogen fertilizer production in case B. The production of 1 kg of soybeans has a global warming impact of 159 g CO_2 equivalent/kg in case A and 163 g CO_2 equivalent/kg in case B. The primary source of greenhouse gases in soybean production is diesel use, amounting to nearly half of the total in both cases. The second largest source of greenhouse gases is gasoline use. Over 65% of the global warming impact is associated with greenhouse gases released from the agricultural use of energy in producing soybeans.

The global warming impact associated with producing 1 kg of alfalfa is 89 g CO_2 equivalent/kg in both cases. The primary source in the global warming impact is greenhouse gases released from diesel used in alfalfa production. About 25% of the global warming impact in producing alfalfa is associated with greenhouse gases released while transporting alfalfa to the biorefinery. The global warming impact associated with producing 1 kg of switchgrass is 124 g CO_2 equivalent/kg in case A and 147 g CO_2 equivalent/kg in case B. About 50% of the global warming impact in producing switchgrass is associated with field emissions of nitrous oxide in both cases. Diesel use is the second most important source of greenhouse gas emissions in both cases. The global warming impact associated with trans-

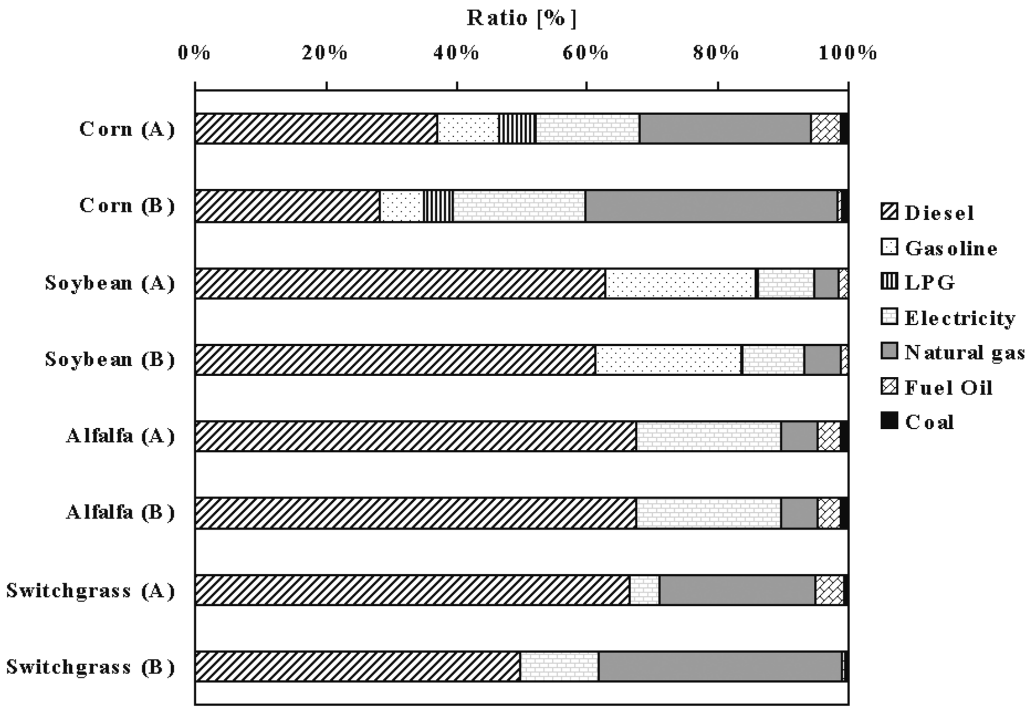

Figure 4 Contribution of energy sources in producing biomass in seven U.S. states in 2000.

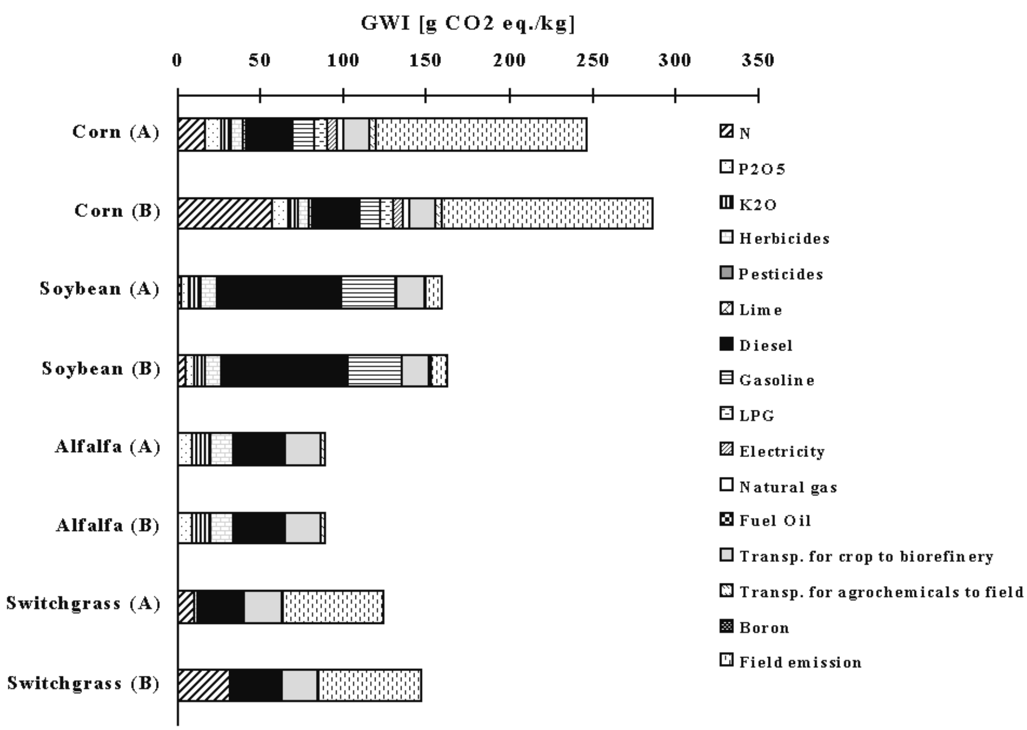

Figure 5 Global warming impact by crop associated with producing biomass in seven U.S. states in 2000 disaggregated by input or process.

porting switchgrass to the biorefinery also contributes significantly to the total global warming impact.

For corn and switchgrass, the most significant greenhouse gas associated with crop production is nitrous oxide, which contributes about 50% of the total global warming impact. Carbon dioxide accounts for essentially all of the remaining impact in both cases. The primary greenhouse gas associated with producing soybeans and alfalfa is carbon dioxide, contributing about 80% of the total global warming impact.

Discussion, Comparisons, and Conclusions

The energy requirement for corn production is available from other studies. These studies (Shapouri et al. 1995, 2002; Pimentel 1991, 2002) estimated the energy requirement for ethanol derived from corn grain and showed, as noted earlier, that the agricultural processes, including corn production and the transportation of corn to biorefinery, account for 27% to 44% of the energy requirement for producing ethanol.

Shapouri and colleagues (1995, 2002) estimated the weighted average cumulative energy requirement for corn production over nine states in the United States based on the HHV. Estimated values were 2.62 MJ/kg corn in 1995 and 2.64 MJ/kg corn in 2002. Pimentel (1991, 2002) estimated the cumulative energy in the United States based on the lower heating value (LHV): 6.26 MJ/kg corn in 1991 and 5.69 MJ/kg corn in 2002. A comparison of these values is shown in figure 6.

Shapouri's values are very close to the cumulative energy requirement for corn production in case B of our study, which is 2.66 MJ/kg. In case A, however, there is a deviation between Shapouri's values and the cumulative energy requirement. This deviation is attributable to the treatment of carbon dioxide in the ammonia plant, in which both ammonia and carbon dioxide are produced. Carbon dioxide is one of the raw materials for producing urea, in which 0.74 to 0.75 kg of carbon dioxide is required to produce 1 kg of urea (EFMA 2000). Thus, the process energy used in the ammonia plant should be allocated to both ammonia and carbon dioxide. This allocation affects the cumulative energy value of nitrogen fertilizer and the cumulative energy requirement for corn production as well.

Even though Pimentel estimated the energy requirement for corn production based on the LHV of the fuel, his values are much higher than those of other researchers who have studied the issue. One reason is that he included the energy requirement for irrigation, assuming about 16% of corn in the United States is grown under irrigation. According to the U.S. Department of Agriculture (NASS 1998), corn production under irrigation accounts for only 1.6% of total corn production in the seven states of this study. These seven states produce about 63% of total U.S. corn production. When Pimentel's energy input value for irrigation (12,862 MJ/ha) is used to estimate the total electricity consumption for irrigation of water in corn production, the irrigation of corn in the United States consumes 3.4 million megawatt-hours of electricity.[13] This figure is equivalent to 0.1% of the total electricity net generation in the United States. This result does not seem reasonable. Furthermore, the corn yield under irrigation is twice that of unirrigated corn (NASS 1998), yet Pimentel used the unirrigated corn yield in both of his studies.

In Pimentel's studies, the cumulative energy value of nitrogen fertilizer (87 MJ/kg N in 1991 and 77 MJ/kg N in 2002) is significantly higher than values in other studies, which range from 42 to 70 MJ/kg N (Borjesson 1996; Refsgaard 1998; Shapouri et al. 1995, 2002; Kongshaug 1998), even though his calculations are based on the LHV. Nitrogen fertilizer is responsible for 25% to 31% of the total energy requirement in Pimentel's study. He also included the energy consumption for manufacturing machinery, which accounted for over 9% of the energy requirement for corn production. The energy requirement for labor (5.2% of the total energy) is included in his latest study (Pimentel 2002), but it is not clear whether the energy input associated with labor comes from nonrenewable energy.

We have used the example of ethanol derived from corn grain to demonstrate the importance of agricultural process information in biobased product systems. Using the energy required for corn production as reported in this article and as

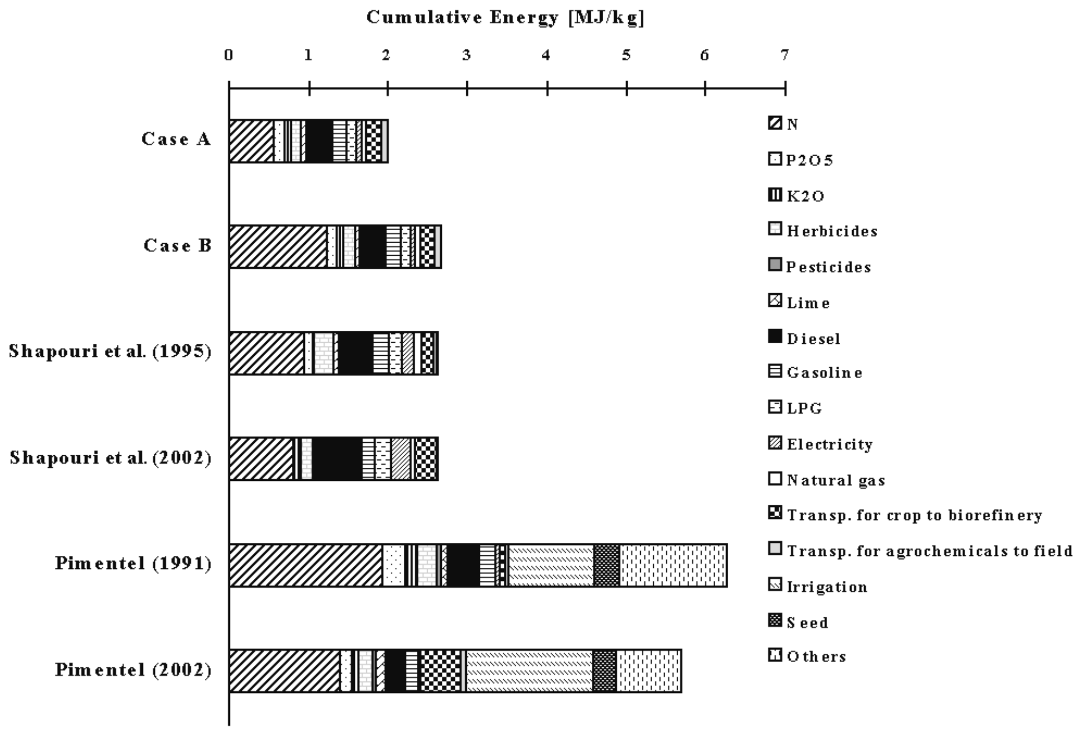

Figure 6 Comparison of the cumulative energy requirement for corn production disaggregated by input or process. (Note: Pimentel's energy values are based on the LHV. Others include the energy requirement for manufacturing machinery, labor, and drying.)

estimated by Pimentel (2002), the energy consumed in producing ethanol is calculated. Before allocation, the energy used in producing 1 kg of ethanol by dry milling ranges from 40 to 42 MJ when the energy values of corn production presented in this article are used, whereas Pimentel's values[14] produce an estimate of 54 MJ, a difference of 26%. When the output mass is used as an allocation factor in dry milling, the net energy value, defined as the energy content of ethanol minus the nonrenewable energy used in producing ethanol, ranges from 7.3 to 8.4 MJ based on the energy demand of corn production estimated in this article and 1.0 MJ in research by Pimentel (2002).[15] The sensitivity of these energy estimates to assumptions about agricultural practice show the importance of agricultural production data as well as allocation procedures in implementing LCA studies of biobased product systems.

Nitrous oxide emission from crop cultivation is a major contributor to the global warming impact for most crop production systems. In this study, nitrous oxide emissions released by the decomposition of crop residues and nitrogen fixed by nitrogen-fixing crops (i.e., soybeans and alfalfa) are not included in the analysis because the conversion to nitrous oxide of nitrogen in crop residues and fixed nitrogen is almost certainly affected by the subsequent crop and its cultivation practices. Uncertainties may also arise in estimating nitrous oxide emissions because they depend on soil nitrogen content, soil moisture content, temperature, precipitation patterns, soil texture, nitrogen fertilizer application, and cultivation practices. Thus, much more site-specific agricultural data are required.

The study presented here estimated the cumulative energy requirement for producing crops used as feedstocks for biobased products and the global warming impact associated with those crop production systems. We note that one cannot directly compare a particular biomass crop to any other crop in terms of either their cumulative energy or their global warming impact as estimated in this study. These crops all have different compositions. Thus the utilization of their intermediates (carbohydrates, protein, lignin, etc.; see figure 1) is different. Essentially, each crop has somewhat different functions. Allocating the environmental burdens to the different functions delivered by the various crops is necessary if we are to directly compare one crop to another. This is the subject of future research.

Notes

1. Editor's note: For an extended assessment of the production of bioethanol from corn stover, see the article by Sheehan and colleagues (2003) in this issue of the *Journal of Industrial Ecology*.
2. Editor's note: For a review of life-cycle assessments of biopolymers, see the article by Dornburg and colleagues (2003) in this issue of the *Journal of Industrial Ecology*.
3. One acre ≈ 0.405 ha ≈ 0.004 km^2
4. Editor's note: For a discussion of opportunities presented by biorefineries, see the column by Realff and Abbas (2003) in this issue of the *Journal of Industrial Ecology*.
5. One gallon ≈ 3.79 L.
6. One megajoule = 106 joules (SI) ≈ 947.8 Btu.
7. The fuel cycle is the series of steps required to produce fuel or to generate electricity. It includes extracting raw materials, processing and cleaning fuel (generating electricity), and transport.
8. The difference between the HHV and lower heating value is the specific enthalpy of vaporization of water, which the HHV includes but the lower heating value does not.
9. Editor's note: For a discussion of industrial production and use of nitrogen-based compounds in the *Journal of Industrial Ecology,* see the article by Febre Domene and Ayres (2001).
10. Unit processes are divided to allocate the environmental burdens to two or more subprocesses according to their functions. The category of subprocesses includes a joint subprocess, in which the allocation procedure is required, and a separated subprocess, in which no allocation procedure is required.
11. One kilogram = 10^3g (SI) ≈ 2.204 lb.
12. One kilometer = 10^3m (SI) ≈ 0.621 mi.
13. Electricity accounted for 31% of the total energy consumed in on-farm pumping of irrigation of water in the United States in 1998 (NASS 1998). The area of cornfields in the United States was about 31 million hectares in 2000, and about 10% of the total corn acreage is irrigated.
14. To produce 1 kg of ethanol, 3.3 kg of corn grain is required. The energy requirement for producing 1 kg of ethanol is 33 MJ (HHV) (Pimentel 2002).
15. In dry milling, about 0.92 kg of distillers' dried grains and solubles is produced along with 1 kg of ethanol. The energy requirement for distributing 1 kg of ethanol is 0.76 MJ (Wang 2000). The energy content of 1 kg of ethanol is 29.8 MJ (HHV).

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