Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels

Jason Hill[*†‡§], Erik Nelson[†], David Tilman[*§], Stephen Polasky[*†], and Douglas Tiffany[†]

Departments of [*]Ecology, Evolution, and Behavior and [†]Applied Economics, University of Minnesota, St. Paul, MN 55108; and [‡]Department of Biology, St. Olaf College, Northfield, MN 55057

Contributed by David Tilman, June 2, 2006

Negative environmental consequences of fossil fuels and concerns about petroleum supplies have spurred the search for renewable transportation biofuels. To be a viable alternative, a biofuel should provide a net energy gain, have environmental benefits, be economically competitive, and be producible in large quantities without reducing food supplies. We use these criteria to evaluate, through life-cycle accounting, ethanol from corn grain and biodiesel from soybeans. Ethanol yields 25% more energy than the energy invested in its production, whereas biodiesel yields 93% more. Compared with ethanol, biodiesel releases just 1.0%, 8.3%, and 13% of the agricultural nitrogen, phosphorus, and pesticide pollutants, respectively, per net energy gain. Relative to the fossil fuels they displace, greenhouse gas emissions are reduced 12% by the production and combustion of ethanol and 41% by biodiesel. Biodiesel also releases less air pollutants per net energy gain than ethanol. These advantages of biodiesel over ethanol come from lower agricultural inputs and more efficient conversion of feedstocks to fuel. Neither biofuel can replace much petroleum without impacting food supplies. Even dedicating all U.S. corn and soybean production to biofuels would meet only 12% of gasoline demand and 6% of diesel demand. Until recent increases in petroleum prices, high production costs made biofuels unprofitable without subsidies. Biodiesel provides sufficient environmental advantages to merit subsidy. Transportation biofuels such as synfuel hydrocarbons or cellulosic ethanol, if produced from low-input biomass grown on agriculturally marginal land or from waste biomass, could provide much greater supplies and environmental benefits than food-based biofuels.

corn | soybean | life-cycle accounting | agriculture | fossil fuel

High energy prices, increasing energy imports, concerns about petroleum supplies, and greater recognition of the environmental consequences of fossil fuels have driven interest in transportation biofuels. Determining whether alternative fuels provide benefits over the fossil fuels they displace requires thorough accounting of the direct and indirect inputs and outputs for their full production and use life cycles. Here we determine the net societal benefits of corn grain (*Zea mays* ssp. *mays*) ethanol and soybean (*Glycine max*) biodiesel, the two predominant U.S. alternative transportation fuels, relative to gasoline and diesel, the fossil fuels they displace in the market. We do so by using current, well supported public data on farm yields, commodity and fuel prices, farm energy and agrichemical inputs, production plant efficiencies, coproduct production, greenhouse gas (GHG) emissions, and other environmental effects.

To be a viable substitute for a fossil fuel, an alternative fuel should not only have superior environmental benefits over the fossil fuel it displaces, be economically competitive with it, and be producible in sufficient quantities to make a meaningful impact on energy demands, but it should also provide a net energy gain over the energy sources used to produce it. We therefore analyze each biofuel industry, including farms and production facilities, as though it were an "island economy" that is a net energy exporter only if the energy value of the biofuel and its coproducts exceeds that of all direct and indirect energy inputs (see Tables 1–6 and *Supporting Text*, which are published as supporting information on the PNAS web site).

Biofuel production requires energy to grow crops and convert them to biofuels. We estimate farm energy use for producing corn and soybeans, including energy use for growing the hybrid or varietal seed planted to produce the crop, powering farm machinery, producing farm machinery and buildings, producing fertilizers and pesticides, and sustaining farmers and their households. We also estimate the energy used in converting crops to biofuels, including energy use in transporting the crops to biofuel production facilities, building and operating biofuel production facilities, and sustaining production facility workers and their households. Outputs of biofuel production include the biofuels themselves and any simultaneously generated coproducts. For purposes of energy accounting, we assign the biofuels themselves an energy content equal to their available energy upon combustion. Coproducts, such as distillers' dry grain with solubles (DDGS) from corn and soybean meal and glycerol from soybeans, are typically not combusted directly; rather, we assign them energy equivalent values.

Results

Net Energy Balance (NEB). Despite our use of expansive system boundaries for energy inputs, our analyses show that both corn grain ethanol and soybean biodiesel production result in positive NEBs (i.e., biofuel energy content exceeds fossil fuel energy inputs) (Fig. 1; see also Tables 7 and 8, which are published as supporting information on the PNAS web site), which reinforce recent findings (1–5). Although these earlier reports did not account for all of the energy inputs included in our analyses, recent advances in crop yields and biofuel production efficiencies, which are reflected in our analyses, have essentially offset the effects of the broad boundaries for energy accounting that we have used. Our results counter the assertion that expanding system boundaries to include energetic costs of producing farm machinery and processing facilities causes negative NEB values for both biofuels (6–8). In short, we find no support for the assertion that either biofuel requires more energy to make than it yields. However, the NEB for corn grain ethanol is small, providing ≈25% more energy than required for its production. Almost all of this NEB is attributable to the energy credit for its DDGS coproduct, which is animal feed, rather than to the ethanol itself containing more energy than used in its production. Corn grain ethanol has a low NEB because of the high energy input required to produce corn and to convert it into ethanol. In contrast, soybean biodiesel provides ≈93% more energy than is required in its production. The NEB advantage of

---

Conflict of interest statement: No conflicts declared.

Abbreviations: NEB, net energy balance; GHG, greenhouse gas; EEL, energy equivalent liter; DDGS, distillers' dry grain with solubles.

[§]To whom correspondence may be addressed at: Department of Ecology, Evolution, and Behavior, University of Minnesota, 1987 Upper Buford Circle, St. Paul, MN 55108. E-mail: hill0408@umn.edu or tilman@umn.edu.

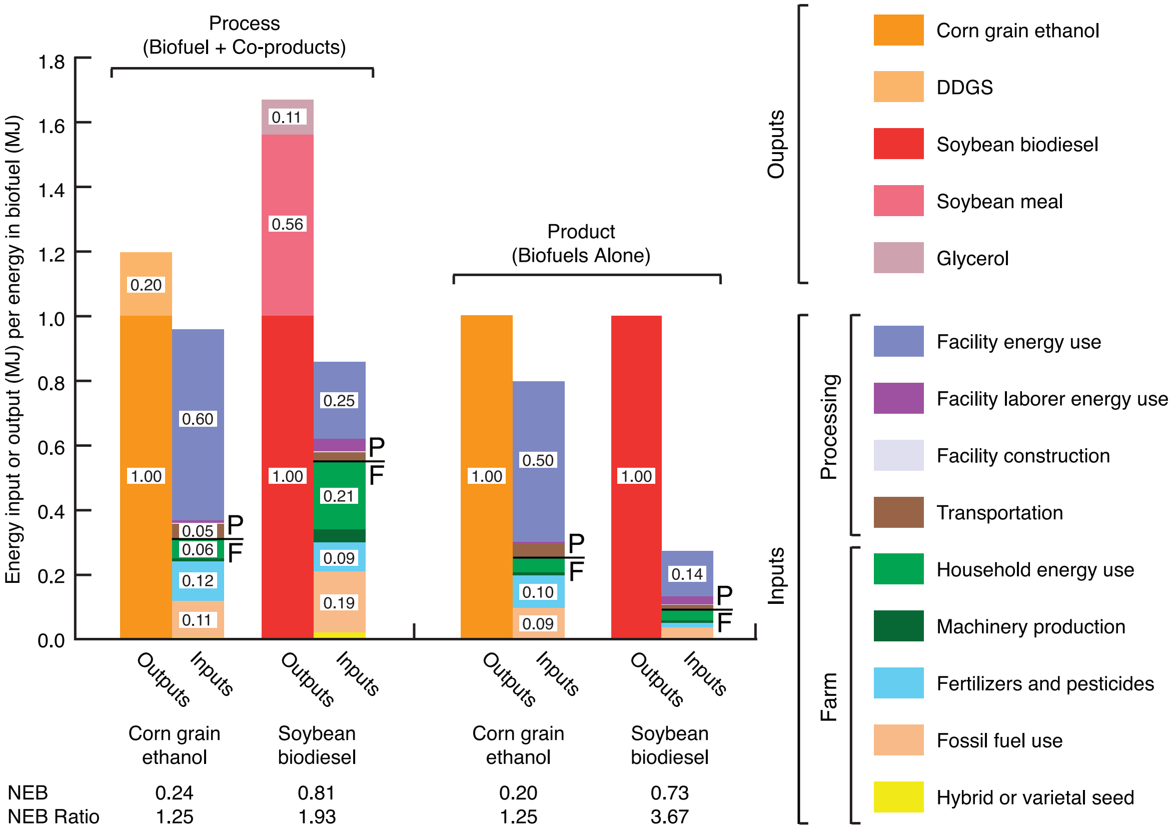

Fig. 1. NEB of corn grain ethanol and soybean biodiesel production. Energy inputs and outputs are expressed per unit energy of the biofuel. All nine input categories are consistently ordered in each set of inputs, as in the legend, but some are so small as to be nearly imperceptible. Individual inputs and outputs of $\geq$0.05 are labeled; values <0.05 can be found in Tables 7 and 8. The NEB (energy output − energy input) and NEB ratio (energy output/energy input) of each biofuel are presented both for the entire production process (*Left*) and for the biofuel only (i.e., after excluding coproduct energy credits and energy allocated to coproduct production) (*Right*).

soybean biodiesel is robust, occurring for five different methods of accounting for the energy credits of coproducts (see Table 9, which is published as supporting information on the PNAS web site).

Life-Cycle Environmental Effects. Both corn and soybean production have negative environmental impacts through movement of agrichemicals, especially nitrogen (N), phosphorus (P), and pesticides from farms to other habitats and aquifers (9). Agricultural N and P are transported by leaching and surface flow to surface, ground, and coastal waters causing eutrophication, loss of biodiversity, and elevated nitrate and nitrite in drinking-water wells (9, 10). Pesticides can move by similar processes. Data on agrichemical inputs for corn and soybeans and on efficiencies of net energy production from each feedstock reveal, after partitioning these inputs between the energy product and coproducts, that biodiesel uses, per unit of energy gained, only 1.0% of the N, 8.3% of the P, and 13% of the pesticide (by weight) used for corn grain ethanol (Fig. 2*a*; see also Table 10, which is published as supporting information on the PNAS web site). The markedly greater releases of N, P, and pesticides from corn, per unit of energy gain, have substantial environmental consequences, including being a major source of the N inputs leading to the “dead zone” in the Gulf of Mexico (11) and to nitrate, nitrite, and pesticide residues in well water. Moreover, pesticides used in corn production tend to be more environmentally harmful and persistent than those used to grow soybeans (Fig. 2*b* and Table 10). Although blending ethanol with gasoline at low levels as an oxygenate can lower emissions of carbon monoxide (CO), volatile organic compounds (VOC), and particulate matter with an aerodynamic diameter $\leq$ 10 μm (PM10) upon combustion, total life-cycle emissions of five major air pollutants [CO, VOC, PM10, oxides of sulfur (SO_x), and oxides of nitrogen (NO_x)] are higher with the “E85” corn grain ethanol–gasoline blend than with gasoline per unit of energy released upon combustion (12). Conversely, low levels of biodiesel blended into diesel reduce emissions of VOC, CO, PM10, and SO_x during combustion, and biodiesel blends show reduced life-cycle emissions for three of these pollutants (CO, PM10, and SO_x) relative to diesel (5).

If CO_2 from fossil fuel combustion was the only GHG considered, a biofuel with NEB > 1 should reduce GHG emissions because the CO_2 released upon combustion of the fuel had been removed from the atmosphere by plants, and less CO_2 than this amount had been released when producing the biofuel. However, N fertilization and incorporation of plant biomass into soil can cause microbially mediated production and release of N_2O, which is a potent GHG (13). Our analyses (see Table 11, which is published as supporting information on the PNAS web site) suggest that, because of the low NEB of corn grain ethanol, production and use of corn grain ethanol releases 88% of the net GHG emissions of production and combustion of an energetically equivalent amount of gasoline (Fig. 2*c*). This result is comparable with a recent study that estimated this parameter at 87% using different methods of analysis (1). In contrast, we find that life-cycle GHG emissions of soybean biodiesel are 59% those of diesel fuel. It is important to note that these estimates assume these biofuels are derived from crops harvested from land already in production; converting intact ecosystems to production would result in reduced GHG savings or even net GHG release from biofuel production.

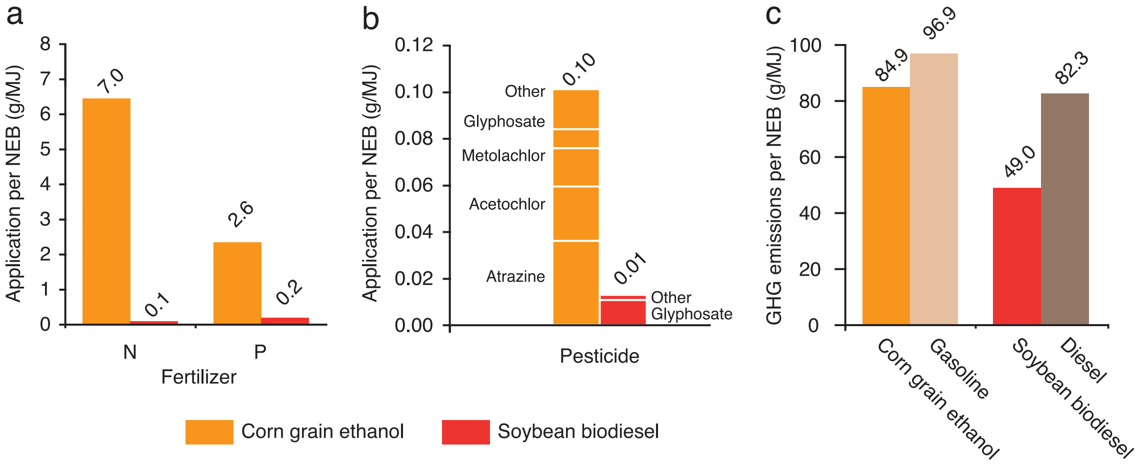

Fig. 2. Environmental effects from the complete production and combustion life cycles of corn grain ethanol and soybean biodiesel. (*a* and *b*) Use of fertilizers (*a*) and pesticides (*b*) per unit of net energy gained from biofuel production (Table 10). (*c*) Net GHG emissions (as CO_2 equivalents) during production and combustion of biofuels and their conventional counterparts, relative to energy released during combustion (Table 11).

Economic Competitiveness and Net Social Benefits. Because fossil energy use imposes environmental costs not captured in market prices, whether a biofuel provides net benefits to society depends not only on whether it is cost competitive but also on its environmental costs and benefits vis-à-vis its fossil fuel alternatives. Subsidies for otherwise economically uncompetitive biofuels are justified if their life-cycle environmental impacts are sufficiently less than for alternatives. In 2005, neither biofuel was cost competitive with petroleum-based fuels without subsidy, given then-current prices and technology. In 2005, ethanol net production cost was $0.46 per energy equivalent liter (EEL) of gasoline (14–16), while wholesale gasoline prices averaged $0.44/liter (17). Estimated soybean biodiesel production cost was $0.55 per diesel EEL (16, 18), whereas diesel wholesale prices averaged $0.46/liter (17). Further increases in petroleum prices above 2005 average prices improve the cost competitiveness for biofuels. Even when not cost competitive, however, biofuel production may be profitable because of large subsidies. In the U.S., the federal government provides subsidies of $0.20 per EEL for ethanol and $0.29 per EEL for biodiesel (19). Demand, especially for ethanol, also comes from laws and regulations mandating blending biofuels in at least some specified proportion with petroleum. Ethanol and biodiesel producers also benefit from federal crop subsidies that lower corn prices (which are approximately half of ethanol production's operating costs) and soybean prices.

Potential U.S. Supply. In 2005, 14.3% of the U.S. corn harvest was processed to produce 1.48×10^{10} liters of ethanol (20, 21), energetically equivalent to 1.72% of U.S. gasoline usage (22). Soybean oil extracted from 1.5% of the U.S. soybean harvest produced 2.56×10^8 liters of biodiesel (20, 23), which was 0.09% of U.S. diesel usage (22). Devoting all 2005 U.S. corn and soybean production to ethanol and biodiesel would have offset 12% and 6.0% of U.S. gasoline and diesel demand, respectively. However, because of the fossil energy required to produce ethanol and biodiesel, this change would provide a net energy gain equivalent to just 2.4% and 2.9% of U.S. gasoline and diesel consumption, respectively. Reaching these maximal rates of biofuel supply from corn and soybeans is unlikely because these crops are major contributors to human food supplies through livestock feed and direct consumption (e.g., high-fructose corn syrup and soybean oil, both major sources of human caloric intake).

Discussion

Among current food-based biofuels, soybean biodiesel has major advantages over corn grain ethanol. Biodiesel provides 93% more usable energy than the fossil energy needed for its production, reduces GHGs by 41% compared with diesel, reduces several major air pollutants, and has minimal impact on human and environmental health through N, P, and pesticide release. Corn grain ethanol provides smaller benefits through a 25% net energy gain and a 12% reduction in GHGs, and it has greater environmental and human health impacts because of increased release of five air pollutants and nitrate, nitrite, and pesticides.

Our analyses of ethanol and biodiesel suggest that, in general, biofuels would provide greater benefits if their biomass feedstocks were producible with low agricultural input (i.e., less fertilizer, pesticide, and energy), were producible on land with low agricultural value, and required low-input energy to convert feedstocks to biofuel. Neither corn grain ethanol nor soybean biodiesel do particularly well on the first two criteria: corn requires large N, P, and pesticide inputs, and both corn and soybeans require fertile land. Soybean biodiesel, however, requires far less energy to convert biomass to biofuel than corn grain ethanol (Fig. 1) because soybeans create long-chain triglycerides that are easily expressed from the seed, whereas in ethanol production, corn starches must undergo enzymatic conversion into sugars, yeast fermentation to alcohol, and distillation. The NEB (and perhaps the cost competitiveness) of both biofuels could be improved by use of low-input biomass or agricultural residue such as corn stover in lieu of fossil fuel energy in the biofuel conversion process.

Nonfood feedstocks offer advantages for these three energetic, environmental, and economic criteria. Switchgrass (*Panicum virgatum*), diverse mixtures of prairie grasses and forbs (24, 25), and woody plants, which can all be converted into synfuel hydrocarbons or cellulosic ethanol, can be produced on agriculturally marginal lands with no (24, 25) or low fertilizer, pesticides, and energy inputs. For cellulosic ethanol, combustion of waste biomass, such as the lignin fractions from biomass feedstocks, could power biofuel-processing plants. Although gains may be somewhat tempered by higher transport energy requirements, higher energy use for construction of larger and more complex ethanol plants, and possibly greater labor needs, resultant NEB ratios may still be >4.0 (26, 27), a major improvement over corn grain ethanol with its NEB ratio of 1.25 and soybean biodiesel with its NEB ratio of 1.93. Cellulosic ethanol is thought to have the potential to become cost competitive with corn grain ethanol through improved pretreatments, enzymes, and conversion factors (28, 29). The NEB ratio for combined-cycle synfuel and electric cogeneration through biomass gasification (30) should be similar to that for cellulosic ethanol and may convert a greater proportion of biomass energy into synfuels and electricity than is possible with cellulosic ethanol. In total, low-input biofuels have the potential to provide much higher NEB ratios and much lower environmental impacts per net energy gain than food-based biofuels.

Global demand for food is expected to double within the coming 50 years (31), and global demand for transportation fuels is expected to increase even more rapidly (32). There is a great need for renewable energy supplies that do not cause significant environmental harm and do not compete with food supply. Food-based biofuels can meet but a small portion of transportation energy needs. Energy conservation and biofuels that are not food-based are likely to be of far greater importance over the longer term. Biofuels such as synfuel hydrocarbons or cellulosic ethanol that can be produced on agriculturally marginal lands with minimal fertilizer, pesticide, and fossil energy inputs, or produced with agricultural residues (33), have potential to provide fuel supplies with greater environmental benefits than either petroleum or current food-based biofuels.

Methods

Energy Use in Crop Production. We use 2002–2004 U.S. Department of Agriculture data on fertilizer, soil treatment, and pesticide application rates for corn (Table 1) and soybean (Table 2) farming. Our estimates of the energy needed to produce each of these agrichemical inputs are derived from recent studies (2–7). We also estimate per-hectare (ha) energy use for operating agricultural equipment, for manufacturing this equipment and constructing buildings used directly in crop production (Table 3), and for producing the hybrid (corn) or varietal (soybeans) seed planted. We transform these estimates of per-hectare energy use into per-biofuel-liter energy use based on crop to biofuel conversion efficiencies of 3,632 liters/ha for corn grain ethanol and 544 liters/ha for soybean biodiesel. Because this island industry cannot operate without laborers, we also estimate the per-biofuel-liter energy use to sustain farm households (Table 4).

Energy Use in Converting Crops to Biofuels. We estimate the energy used to build the facilities used to convert crops to biofuels (Table 6), transport crops to these facilities, power these facilities, and transport biofuels to their point of end use (Table 5). As with farm labor, we estimate the energy used by households of industry laborers (Table 4).

Energy Yield from Biofuel Production. The energy output of biofuel production includes the combustible energy of biofuels themselves and energy equivalent values for coproducts that typically have uses other than as energy commodities (Table 5). We assign coproduct credits as follows. For DDGS and glycerol we use an "economic displacement" method whereby we calculate the energy required to generate the products for which each serves as a substitute in the marketplace (i.e., corn and soybean meal for DDGS and synthetic glycerol for soybean-derived glycerol). For soybean meal, which does not have an adequate substitute in the marketplace based on both its availability and protein quality, we estimate its coproduct energy credit by a "mass allocation" method as the fraction of energy, based on the relative weight of the soybean meal to the entire soybean weight processed, used to grow soybeans and produce soybean meal and oil. We also apply alternative methods of calculating coproduct credits including issuing energy values based on caloric content and market value (Table 9).

We determine the NEB of a biofuel by subtracting the value of all fossil energy inputs used in producing the biofuel from the energy value of the biofuel and its coproducts. Similarly, we calculate the NEB ratio by dividing the sum of these outputs over that of the inputs.

Environmental Effects. When measuring the life-cycle environmental impacts of each biofuel, we expand the island industry model to include total net emissions from biofuel combustion as well as production. Given the NEB of each biofuel and current fertilizer and pesticide application rates, we calculate for each biofuel the amount of each agricultural input applied per unit of energy gained by producing the biofuel (Table 10). For our estimates of GHG savings in producing and combusting each biofuel in lieu of a fossil fuel, we first calculate the life-cycle GHG savings from displacing the fossil fuel (i.e., from the energy gained in producing the biofuel) and then add to this amount the net GHG emissions released on the farm.

We thank K. Bauer, K. Harpankar, D. Legvold, G. Koerbitz, and D. Masterson for assistance and C. Umbanhowar, Jr., S. Suh, and A. Keating for comments. This work was supported by grants from the Initiative for Renewable Energy and the Environment (to S.P. and D. Tilman), the Howard Hughes Medical Institute (J.H.), National Science Foundation Grant DEB-0080382 (to D. Tilman), and the Bush Foundation (D. Tilman and S.P.).

1. Farrell, A. E., Plevin, R. J., Turner, B. T., Jones, A. D., O'Hare, M. & Kammen, D. M. (2006) *Science* **311,** 506–508.
2. Wang, M., Saricks, C. & Wu, M. (1997) *Fuel-Cycle Fossil Energy Use and Greenhouse Gas Emissions of Fuel Ethanol Produced from U.S. Midwest Corn* (Argonne Natl. Lab., Argonne, IL).
3. Graboski, M. S. (2002) *Fossil Energy Use in the Manufacture of Corn Ethanol* (National Corn Growers Association, St. Louis, MO).
4. Shapouri, H., Duffield, J., McAloon, A. & Wang, M. (2004) *The 2001 Net Energy Balance of Corn-Ethanol* (U.S. Dept. of Agriculture, Washington, DC).
5. Sheehan, J., Camobreco, V., Duffield, J., Graboski, M. & Shapouri, H. (1998) *Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus* (Natl. Renewable Energy Lab., Golden, CO), NREL Publ. No. SR-580-24089.
6. Pimentel, D. (2003) *Nat. Resources Res.* **12,** 127–134.
7. Patzek, T. W. (2004) *Crit. Rev. Plant Sci.* **23,** 519–567.
8. Pimentel, D. & Patzek, T. W. (2005) *Nat. Resources Res.* **14,** 65–76.
9. Vitousek, P. M., Aber, J. D., Howarth, R. W., Likens, G. E., Matson, P. A., Schindler, D. W., Schlesinger, W. H. & Tilman, D. G. (1997) *Ecol. Appl.* **7,** 737–750.
10. Carpenter, S. R., Caraco, N. F., Correll, D. L., Howarth, R. W., Sharpley, A. N. & Smith, V. H. (1998) *Ecol. Appl.* **8,** 559–568.
11. Downing, J. A., Baker, J. L., Diaz, R. J., Prato, T., Rabalais, N. N. & Zimmerman, R. J. (1999) *Gulf of Mexico Hypoxia: Land and Sea Interactions.* (Council for Agricultural Sci. and Technol., Ames, IA).
12. Brinkman, N., Wang, M., Weber, T. & Darlington, T. (2005) *Well-to-Wheels Analysis of Advanced Fuel/Vehicle Systems: A North American Study of Energy Use, Greenhouse Gas Emissions, and Criteria Pollutant Emissions* (Argonne Natl. Lab., Argonne, IL).
13. Robertson, G. P., Paul, E. A. & Harwood, R. R. (2000) *Science* **289,** 1922–1925.
14. U.S. Department of Agriculture: National Agricultural Statistics Service (2005) *Feed Grains Database* (Dept. of Agriculture, Washington, DC).
15. Tiffany, D. G. & Eidman, V. R. (2005) in *Agriculture as a Producer and Consumer of Agriculture*, eds. Outlaw, J., Collins, K. J. & Duffield, J. A. (CABI, Cambridge, MA).
16. U.S. Department of Energy, Energy Information Administration (2006) *Natural Gas Monthly* (Dept. of Energy, Washington, DC), DOE Publ. No. EIA-0130(2006/04).
17. U.S. Department of Energy, Energy Information Administration (2006) *Petroleum Marketing Monthly* (Dept. of Energy, Washington, DC), DOE Publ. No. EIA-0380(2005/06).
18. Fortenbery, T. R. (2005) *Biodiesel Feasibility Study: An Evaluation of Biodiesel Feasibility in Wisconsin* (Univ. of Wisconsin, Madison, WI), Department of Agricultural and Applied Economics Staff Paper No. 481.

19. Shapouri, H. & Gallagher, P. (2005) *USDA's 2002 Ethanol Cost-of-Production Survey* (Dept. of Agriculture, Washington, DC), Agriculture Economic Rep. No. 841.
20. Interagency Agricultural Projections Committee (2006) *USDA Agricultural Baseline Projections to 2015* (Dept. of Agriculture, Washington, DC), DOE Publ. No. OCE-2006-1.
21. Renewable Fuels Association (2006) *Industry Statistics* (Renewable Fuels Assoc., Washington, DC).
22. U.S. Department of Energy, Energy Information Administration (2006) *Annual Energy Outlook 2006 With Projections to 2030* (Dept. of Energy, Washington, DC), DOE Publ. No. EIA-0383(2006).
23. National Biodiesel Board (2005) *How Much Biodiesel Has Been Sold in the U.S.*? (Natl. Biodiesel Board, Jefferson City, MO).
24. Tilman, D., Reich, P. B., Knops, J. M. H., Wedin, D., Mielke, T. & Lehman, C. (2001) *Science* **294,** 843–845.
25. Tilman, D., Reich, P. B. & Knops, J. M. H. (2006) *Nature* **441,** 629–632.
26. Sheehan, J., Aden, A., Paustian, K., Killian, K., Brenner, J., Walsh, M. & Nelson, R. (2004) *J. Ind. Ecol.* **7,** 117–146.
27. Morey, R. V., Tiffany, D. & Hatfield, D. (2005) *Biomass for Electricity and Process Heat at Ethanol Plants* (Am. Soc. Agricult. Biol. Engineers, St. Joseph, MI), ASABE Paper No. 056131.
28. Aden, A., Ruth M., Ibsen, K., Jechura, J., Neeves, K., Sheehan, J., Wallace, B., Montague, L., Slayton, A. & Lukas, J. (2002) *Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover* (Natl. Renewable Energy Lab., Golden, CO), NREL Publ. No. TP-510-32438.
29. Tiffany, D. G. & Eidman, V. R. (2005) in *Food, Agriculture, and the Environment: Economic Issues*, eds. Defrancesco, E., Galletto, L. & Thiene, M. (FrancoAngeli, Milan), pp. 325–340.
30. Larson, E. D., Williams, R. H. & Jin, H. (2006) *Fuels and Electricity From Biomass With* CO_2 *Capture and Storage*. Presented at the 8th International Conference on Greenhouse Gas Control Technologies, 2006, Trondheim, Norway.
31. Fedoroff, N. V. & Cohen, J. E. (1999) *Proc. Natl. Acad. Sci. USA* **96,** 5903–5907.
32. U.S. Department of Energy, Energy Information Administration (2006) *International Energy Outlook* (Dept. of Energy, Washington, DC), DOE Publ. No. EIA-0484 (2006).
33. Perlack, R. D., Wright, L. L., Turhollow, A. F., Graham, R. L., Stokes, B. J. & Erbach, D. C. (2005) *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply* (Oak Ridge Natl. Lab., Oak Ridge, TN), ORNL Publ. No. TM-2005/66.

Table 1. Farm energy inputs into corn grain ethanol production

	Application rate, kg/ha	Production energy requirement, MJ/kg	Per hectare energy usage, MJ/ha	Input energy in ethanol production, MJ/liter*
Hybrid seed	-	-	215[†] (2)	0.06
Nitrogen	146.1	51.47[‡] (2, 4, 5)	7,523	2.07
Phosphorus	53.1	9.17 (3-5)	486	0.13
Potash	65.6	5.96 (2-5)	391	0.11
Lime	-	-	313[§] (2, 5, 6)	0.09
Herbicide	2.23	319[¶] (3-6)	713	0.20
Insecticide	0.08	325 (3-6)	26	0.01
Fossil fuel	-	-	8,484[‖]	2.34
Farm capital	-	-	769 (Table 3)	0.21
Household	-	-	-	1.18 (Table 4)
Total				6.39

Application rates of nitrogen, phosphorus, potash, herbicides, and insecticides are 2003 averages of the nine top corn-producing states (IL, IN, IA, MI, MN, NE, OH, SD, and WI) weighted by state production (1). Production energy requirements are average values of five studies representing recent independent estimates of corn grain ethanol NEB (2-6), with exceptions as noted.

* The 2000-2004 average annual yield of the top nine corn-producing states weighted by their total production is 9,296 kg/ha (7, 8). These nine states accounted for 79.1% of domestic corn production in 2004. The dry-mill conversion efficiency of ethanol from corn is 0.3908 liters/kg, which is an average of three estimates (2-4). We exclude wet-milling conversion efficiencies (5). The dry-milling process currently accounts for 75% of the corn grain ethanol production market share and is expected to increase (9). We omit estimates based on older technologies (e.g., 0.3726 liters/kg) (6) that are dramatically lower than recently documented dry-mill plant efficiencies (e.g., 0.3979 liters/kg) (9, 10).

[†] Hybrid corn seed, which is planted to grow the corn used to generate ethanol, requires additional production steps when grown, processed, and distributed. Our estimate of the energy required to produce hybrid corn seed is derived from the only study that both uses current USDA data and provides the formula used to derive this estimate (2). We exclude studies that do not account for the energy to grow the hybrid seed (4), are based on research > 25 years old (6), do not thoroughly explain how they derived their estimate (3), or are not well supported (5).

[‡] Estimates of fertilizer production energy requirements from one study (6) are excluded because they are from sources that do not reflect current domestic production efficiencies (e.g., the Food and Agriculture Organization, which is not specific to the U.S.). Additionally, for nitrogen we exclude an estimate that includes transportation energy (3), and for phosphorus we exclude an estimate that is substantially lower than others (2).

[§] Unlike fertilizer and pesticide use, lime use is not systematically reported by the USDA. Therefore, we rely on other studies for lime application rates as well as energy intensity. We exclude those studies that either exclude this input analysis (4) or have too low a value (3). We divide liming energy inputs equally between corn and soybean production.

[¶] We exclude the estimate that provides a combined pesticide input (2) because it is not parsed into insecticides and herbicides.

[‖] This category includes fossil fuels directly used in crop production (diesel, gasoline, electricity, natural gas, and LP gas), custom work, farm-related transportation, and personal commutes. We exclude an estimate of fossil fuel use that is substantially lower than those of the other studies (4). We prorate the energy for irrigation of one of the studies (6) to reflect that only 15% of corn acreage in the nine states is irrigated. We exclude estimates for custom work that include worker sustenance energy (5, 6), which we account for separately as part of our expanded category of household energy usage. Our farm-related transportation estimate is from one study (2), and we specifically exclude another (6) because the assumption that machinery, fuels, and seeds were shipped an estimated 1,000 km is unrealistic. Our personnel commute energy estimate is based on the only study that includes this input (5), although we modify this estimate by using our corn yield rate and corn to ethanol conversion rate.

Table 2. Farm energy inputs into soybean biodiesel production

	Application rate, kg/ha	Production energy, MJ/kg	Per hectare energy use, MJ/ha	Input energy in biodiesel production, MJ/liter*
Varietal seed	-	-	420[†]	0.77
Nitrogen	5.7	51.47[‡] (2, 4, 5)	291	0.53
Phosphorus	17.2	9.17 (3-5)	158	0.29
Potash	30.1	5.96 (2-5)	179	0.33
Lime	-	-	313[§]	0.58
Pesticide	1.2	475[¶]	605	1.11
Fossil fuel	-	-	3,361[‖]	6.18
Farm capital	-	-	769 (Table 3)	1.41
Household	-	-	-	6.79 (Table 4)
Total				17.99

Fertilizer application rates are 2002 and 2004 U.S. annual averages (11, 12). Pesticide application rates are 2004 weighted averages of the top 11 soybean-producing states (AR, IL, IN, IA, KS, MN, MO, NE, ND, OH, and SD) (12).

[*] The 2000-2004 average yield of the 31 soybean-producing states weighted by total production is 2,661 kg/ha (7, 8), and 4.89 kg of soybeans are crushed per liter of biodiesel produced.

[†] Given a weighted soybean yield of 2,661 kg/ha and a national average seeding rate of 76.1 kg/ha (13), 2.86% of one year's crop can be used to plant the same acreage the next year. We assume that growing, processing, packaging, and transporting soybean seed for planting requires 150% of the energy used to grow soybeans used for feed or industrial purposes (14). We therefore estimate the energy to produce the soybeans needed to plant 1 ha of land as 4.29% the energy to produce 1 ha of soybeans for direct use for feed and fuel (9,791 MJ/ha).

[‡] Fertilizer production energy is the same as in corn production.

[§] Because we assume corn and soybeans are grown in rotation, we divide the liming energy input between corn and soybeans equally.

[¶] In 2004, glyphosate, which requires approximately 475 MJ/kg to produce and distribute (15), accounted for 81% of all pesticide use (12). We assume that the energy to produce glyphosate is similar in all pesticides used in soybean farming; however, this is likely an overestimate as glyphosate tends to be more costly in energy terms to produce than other pesticides (2).

[‖] Estimates of farm fossil fuel use for truck and tractor use, irrigation, and drying were taken from 2002 ERS-USDA survey data (16) and weighted by average state production. Energy content and average usage rates are as follows: diesel (36.6 MJ/liter and 38.4 liters/ha), gasoline (32.05 MJ/liter and 12.2 liters/ha), electricity (3.6 MJ/kWh and 69.4 kWh/ha), natural gas (37.3 MJ/m^3 and 3.7 m^3/ha), and LP gas (25.5 MJ/liter and 3.7 liters/ha). We also estimate custom work diesel use of 6.6 liters/ha (14), and farm-related transportation and personal commute energy use equal to those of corn farming.

Table 3. Energy to produce machinery and capital used on a representative 120-ha farm with a corn/soybean crop rotation

Machinery and capital	Weight of equipment, Mg	Production energy, GJ*	Per hectare annual production energy, MJ/ha/yr[†]	Equipment energy per unit of biofuel production, MJ/liter[‡] Ethanol	Biodiesel
Tractor - large	10.2	383	210	0.029	0.193
Tractor - small	5.6	210	115	0.016	0.106
Field cultivator	2.4	89	49	0.007	0.045
Chisel plow/ripper	3.6	134	74	0.010	0.068
Planter	3.4	128	70	0.010	0.064
Combine	11.9	445	244	0.034	0.224
Soybean combine head	2.8	104	57	0.008	0.052
Corn combine head	3.6	136	75	0.010	0.069
Gravity box (x4)	6.6	248	136	0.019	0.125
Auger	0.8	28	15	0.002	0.014
Grain bin (x3)	9.5	358	197	0.027	0.181
Irrigation[§]	4.8	179	98	0.014	0.090
Sprayer	0.5	17	9	0.001	0.008
Agricultural buildings	9.1	341	187	0.026	0.172
Total	74.8	2,800	1,538	0.212	1.414

* For each piece of machinery and equipment, we assume for purposes of calculating its embodied energy that it consist entirely of steel. It takes 25 MJ/kg to produce steel (17, 18) and an additional 50% energy use for assembly (2).

[†] All items are assumed to have a service life of 15 years.

[‡] We use values of 3,632 liters of ethanol and 544 liters of biodiesel produced per hectare.

[§] We assume that 15% of farms have two 50-ha center pivot irrigation systems (3).

Table 4. Farm and biofuel labor household energy use

	Farm household members in biofuel production*	Nonfarm labor household members in biofuel production[†]	Annual U.S. non-biofuel per capita energy consumption, MJ[‡]	Total household energy use in biofuel production, MJ	2005 U.S. biofuel production, liters	Total household energy use per unit of biofuel production, MJ/liter[§]	Allocated household energy use on farm / off farm, MJ/liter
Corn grain ethanol	49,160	6,250	3.54×10^5	1.96×10^{10}	1.48×10^{10}	1.33	1.18 / 0.15
Soybean biodiesel	4,900	774	3.55×10^5	2.01×10^9	2.56×10^8	7.87	6.79 / 1.08

* In 2005, 4.71×10^6 ha were devoted to corn farming for ethanol (19). As the average farm size was 120 ha in the top nine corn-producing states (20), the equivalent of 3.93×10^4 farms provided the corn for ethanol production. Approximately 2.56×10^8 liters of biodiesel were produced in 2005 (21), 90% of which derived from soybean oil. With an average farm size of 120 ha in the top 15 soybean-producing states (20), the equivalent of 3.91×10^3 farms were devoted to growing soybeans for biodiesel production. We assume an average of 2.5 people on each farm (22) and that 50% of farm household labor is devoted to farming (23).

[†] An average of 40 people work in an ethanol plant, which includes those involved in corn and ethanol transportation (24), and as of 2005 there were ≈100 ethanol plants in the U.S. (25). Off-farm soybean biodiesel production is done at both soybean crushing and soybean oil conversion facilities. With ≈75 crushing facilities nationwide and 50 laborers at each facility (George Anderson, personal communication), 3,750 workers were involved in crushing; however, only 1.65% of crushed soybeans were needed to produce the soybean oil used to make biodiesel. We assume 10 larger and 35 smaller soybean oil conversion facilities nationally, each with 25 and 5 laborers, respectively (26). The total off-farm laborers in corn grain ethanol and soybean biodiesel production are, therefore, 4,000 and 487, respectively. Given the 2000-2005 annual average of employment/population ratio of 63% (27), we assume that each laborer supports 1.59 people.

[‡] The U.S. energy consumption in 2004 was 1.05×10^{14} MJ (28). Also, 1.48×10^{10} liters of corn grain ethanol (19) and 2.56×10^8 liters of soybean biodiesel (21) were produced in 2005 at 20.38 and 28.37 MJ/liter, respectively. Therefore, the total national energy usage excluding that used in the entire ethanol production cycle was 1.05×10^{14} MJ, or 99.7% of national energy consumption. For biodiesel, the corresponding estimates are 1.05×10^{14} MJ and 100.0%. The average U.S. population in 2004 was 2.96×10^8 people (29).

[§] Average annual household energy use divided by average annual industry biofuel production.

Table 5. Off-farm energy inputs/outputs of soybean biodiesel and corn grain ethanol production and coproduct energy credit

	Production energy, MJ/liter			
	Corn grain ethanol		Soybean biodiesel	
	Input	Output	Input	Output
Crop and biofuel transportation*	1.07		1.17	
Conversion of crop to biofuel†	12.73		8.08	
Production facility capital	0.04		0.06	
Nonfarm household energy use	0.15		1.08	
Energy in biofuel‡		21.26		32.93
Coproduct credit§		4.31		21.94

[*] Energy use to transport corn from the farm to ethanol plants and to transport ethanol from the plants to end users is an average of five studies (2-6). For soybean biodiesel production, we used reported energy input values for transporting soybeans from farm to crushing facility, soybean oil from crushing facility to soybean oil conversion facility, and biodiesel from the soybean oil conversion facility to the point of use (14).

[†] Dry-mill ethanol production energy use is an average of estimates from three studies (2-4), excluding the study that assumes wet-milling (5) and that which includes in this value energy to produce an ethanol plant (6), which we calculate separately. For soybean biodiesel, we use current steam and electricity production efficiencies to estimate the energy required to produce oil and meal from seed at a crushing plant and convert the oil to biodiesel and glycerol at a conversion facility (George Anderson, personal communication). At the crushing plant, 0.260 kg of steam and 0.027 kWh of electricity are required per kg of soybeans for seed preparation, oil extraction, and meal production. At the conversion facility, 0.395 kg of steam and 0.024 kWh of electricity are needed per kg of soybean oil for degumming and transesterification. Energy inputs for steam and electricity are 2.44 MJ/kg and 3.60 MJ/kWh. We include production energy of solvents and reagents used in processing (i.e., hexane, methanol, sodium hydroxide, hydrochloric acid, and sodium methoxide) (14).

[‡] The combustible energy of corn grain ethanol and soybean biodiesel are assumed to be 21.26 MJ/liter (2-6) and 32.93 MJ/liter (14), respectively.

[§] *Coproduct credit for DDGS*: Enough DDGS is produced per liter of ethanol to displace 0.78 kg of corn and 0.59 kg of soybean meal (30). As it takes 2.04 and 4.60 MJ to produce 1 kg of corn and 1 kg soybean meal, respectively, 4.31 MJ are credited per liter of ethanol. *Coproduct credit for soybean meal*: With a soybean oil content of 18%, the soybean meal coproduct credit is 18.43 MJ per liter of biodiesel, which is 82% of the energy used to grow soybeans, transport them to a crushing facility, extract their oil, and prepare the meal (14). Energy inputs for soybean oil transportation and conversion, and biodiesel distribution are not allocated as these steps are specific to biodiesel production from soybean oil. *Coproduct credit for glycerol:* 0.071 kg of glycerol is produced per liter of soybean biodiesel. It takes 49.5 MJ/kg to produce synthetic glycerol (31). Therefore, the coproduct credit of glycerol per liter of biodiesel is 3.51 MJ. Because synthetic glycerol is of a higher purity than raw glycerol, however, this coproduct credit overestimates the displacement energy.

Table 6. Material and building energy requirements for constructing ethanol and biodiesel production facilities

	Dry mill ethanol plant			Soybean crushing plant			Biodiesel conversion facility		
Building material	Material weight, Mg	Embodied energy, GJ	Ethanol input energy, kJ/liter*	Material weight, Mg	Embodied energy, GJ	Biodiesel input energy, kJ/liter†	Material weight, Mg	Embodied energy, GJ	Biodiesel input energy, kJ/liter
Concrete	14,200	42.6	18.8	17,800	53.3	21.8	3,600	10.7	4.7
Structural carbon steel	635	23.8	10.5	907	2.7	1.1	272	10.2	4.5
Building siding carbon steel	181	6.8	3.0	272	10.2	4.2	91	3.4	1.5
Carbon steel liquid storage tanks	91	3.4	1.5	91	3.4	1.4	272	10.2	4.5
Stainless steel liquid storage tanks	272	10.8	4.8	45	1.8	0.7	45	1.8	0.8
Stainless steel piping	91	3.6	1.6	45	1.8	0.7	45	1.8	0.8
Carbon steel piping	23	0.9	0.4	45	1.7	0.7	0	0.0	0.0
Other stainless steel equipment	227	9.0	4.0	340	13.5	5.5	113	4.5	2.0
Total		100.9	44.4		88.4	36.1		42.6	18.7

The throughput of each facility is as follows: dry mill ethanol plant (1.14 × 10^8 liters of ethanol/yr), soybean crushing plant (6.0 × 10^8 kg of soybeans/yr) and biodiesel conversion facility (1.14 × 10^8 liters of biodiesel/yr). Plant material requirements for representative facilities were provided by industry sources (George Anderson and Mark Vermeer, personal communications). The energy used to produce concrete, carbon steel, and stainless steel is assumed to be 2, 25, and 26.5 MJ/kg, respectively (17, 18, 32). We include an additional 50% energy input for construction and assembly. We assume a 20-year plant life for all facilities.

* Allocation calculated by embodied energy divided by throughput.

† A total of 4.89 kg of soybeans are crushed per liter of biodiesel produced.

Table 7. Biofuel production energy inputs (MJ/liter) per unit of biofuel energy output (MJ/liter)

	Corn grain ethanol		Soybean biodiesel		
Production stage	Ethanol	DDGS	Biodiesel	Soybean meal	Glycerol
Production of hybrid or variety seed for planting	0.002	0.000	0.004	0.019	0.000
Farm fossil fuel energy use	0.091	0.019	0.031	0.154	0.003
Farm fertilizer and pesticide production	0.102	0.021	0.014	0.071	0.001
Farm machinery production	0.008	0.002	0.007	0.035	0.001
Farm household energy use	0.046	0.009	0.034	0.169	0.004
Processing facility energy use	0.498	0.101	0.141	0.089	0.015
Processing facility construction	0.002	0.000	0.001	0.001	0.000
Processing facility laborer household energy use	0.006	0.001	0.026	0.003	0.003
Crop and biofuel transportation	0.042	0.008	0.015	0.018	0.002
Total	0.797	0.162	0.273	0.560	0.029

Energy input numbers are from Tables 1-6. Biofuel energy output numbers are from Table 5. Estimates from this table are presented in Fig. 1.

Table 8. Energy inputs to produce biofuels and coproducts (MJ/liter) per unit of biofuel energy output (MJ/liter)

	Corn grain ethanol		Soybean biodiesel	
Product	Input	Output	Input	Output
Biofuel	0.797	1	0.273	1
Coproducts	0.162	0.203	0.589	0.666
Total	0.959	1.203	0.861	1.666

Input energy allocation, coproduct energy credits, and energy output numbers are from Table 5. Estimates from this table are presented in Fig. 1.

Table 9. Effects of alternative coproduct calculations on NEB ratios

Biofuel	Base	No credit	Mass balance	Energy content	Market value
Corn grain ethanol	1.25	1.04	1.52	1.71	1.21
Soybean biodiesel	1.93	1.16	1.83	3.38	1.81

In addition to our base NEB ratio detailed in Table 5, we estimate the coproduct credit for both biofuels using mass balance, energy content, and market value. All three methods assume 0.914 kg of DDGS are made per kg of ethanol, and 4.56 kg of soybean meal and 0.08 kg of glycerol are produced per kg of biodiesel. For the mass balance method, the coproduct credit for each coproduct is equal to the energy input of all production steps leading to creation of the coproduct multiplied by the relative weight of the coproduct to the biofuel or biofuel intermediate product. For the energy content method, the coproduct credit is the amount of inherent energy (low heat value) within each product assuming complete combustion at 90% boiler efficiency (DDGS = 20.79 MJ/kg; soybean meal = 16.84 MJ/kg; glycerol = 16.55 MJ/kg) (33). For the market value method, the coproduct credit is equal to the relative value (2002-2004 wholesale averages) of each of the products of biofuel production (ethanol = \$0.37/kg; DDGS = \$0.10/kg; biodiesel = \$0.52/kg; soybean meal = \$0.22/kg; raw glycerol = \$0.88/kg) (34). Values shown are NEB ratios.

Table 10. Agricultural inputs in corn and soybean farming per unit of energy gained from biofuel production

Agricultural input	Application rate, kg/ha	Input per energy gained by biofuel production, g/MJ*	Input per energy gained by biofuel production allocated to biofuel, g/MJ†
Corn grain ethanol			
Nitrogen fertilizers	146.1	7.75	6.44
Phosphorus fertilizers	53.1	2.82	2.34
Pesticides	2.3	0.12	0.10
Soybean biodiesel			
Nitrogen fertilizers	5.6	0.39	0.06
Phosphorus fertilizers	17.2	1.19	0.19
Pesticides	1.2	0.08	0.01

* We assume corn grain ethanol and soybean biodiesel yields of 3,632 and 544 liters/ha, respectively. The NEB of corn grain ethanol and soybean biodiesel is 5.19 and 26.50 MJ/liters, respectively.

† As shown in Table 7, 83.1% of the agricultural inputs into corn farming are attributable to the ethanol itself [0.797 / (0.797 + 0.162)]. For soybean biodiesel, 82% of the agricultural inputs into soybean production are allocated to soybean meal, and of the remaining 18%, 90.4% is allocated to biodiesel [0.273 / (0.273 + 0.029)]; therefore, 16.3% of the fertilizer and pesticide use is attributable to biodiesel.

Table 11. Net greenhouse gas (GHG) savings per energy equivalent liter of biofuels used in lieu of fossil fuels

	Total life cycle GHG emissions from the fossil fuel that is displaced*	Fossil fuel GHG emissions avoided by using biofuel instead of fossil fuel†	Farm N_2O emissions in biofuel production ‡	Farm CH_4 mitigation in biofuel production§	Farm CO_2 liming emissions in biofuel production¶	Net GHG emissions saved by producing and using biofuel‖	Net fraction of GHG emissions saved by producing and using biofuel, %
Corn grain ethanol	96.90	19.66	5.60	0.43	2.48	12.02	12.4
Soybean biodiesel	82.32	39.76	4.72	0.36	2.09	33.32	40.5

All values are expressed in CO_2 equivalent g/MJ.

* Total life cycle GHG emissions of gasoline (for corn grain ethanol) or diesel (for soybean biodiesel) (35).

† Total life cycle GHG emissions from the fossil fuel that is displaced multiplied by the fossil fuel displacement rate of the biofuel, which is defined as $1 - \frac{1}{\text{NEB Ratio}}$. Displaced fossil fuel GHG emissions may vary depending on the specific fossil fuels used in production (e.g., coal, natural gas, gasoline, and diesel). This accounts for the net energy gain from each biofuel but not the GHG release (N_2O and CO_2) or mitigation (CH_4) in crop production, which are estimated in the following two columns.

‡ With conventional tillage on a corn/soybean/wheat rotation farm, CO_2 equivalent N_2O emissions are 52 g/m^2 (36). As 3,632 liters of corn grain ethanol and 544 liters of soybean biodiesel are produced per hectare, 143 and 955 g of CO_2 equivalent N_2O are released per liter of ethanol and biodiesel, respectively. With a low heat value of 21.26 MJ/liter for ethanol and 32.93 MJ/liter for biodiesel, 6.73 and 29.03 g of CO_2 equivalent N_2O are released per MJ of ethanol and biodiesel, respectively. As in Table 10, 83.1% of this 6.73 g for corn farming is allocated to ethanol, and 16.3% of this 29.35 g is allocated to biodiesel.

§ Calculations are the same as for N_2O except that rather than release GHG, these agricultural practices mitigate 4 g/m^2 of CO_2 equivalent CH_4 emissions (36).

¶ Calculations are the same as for N_2O and CH_4 except for that these agricultural practices cause CO_2 emissions of 23 g/m^2 from liming (36).

‖ Net GHG emissions saved by producing and using biofuel equals the fossil fuel GHG emissions avoided minus the farm CO_2 (from liming) and N_2O emissions in biofuel production plus the farm CH_4 mitigation in biofuel production.