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

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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

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

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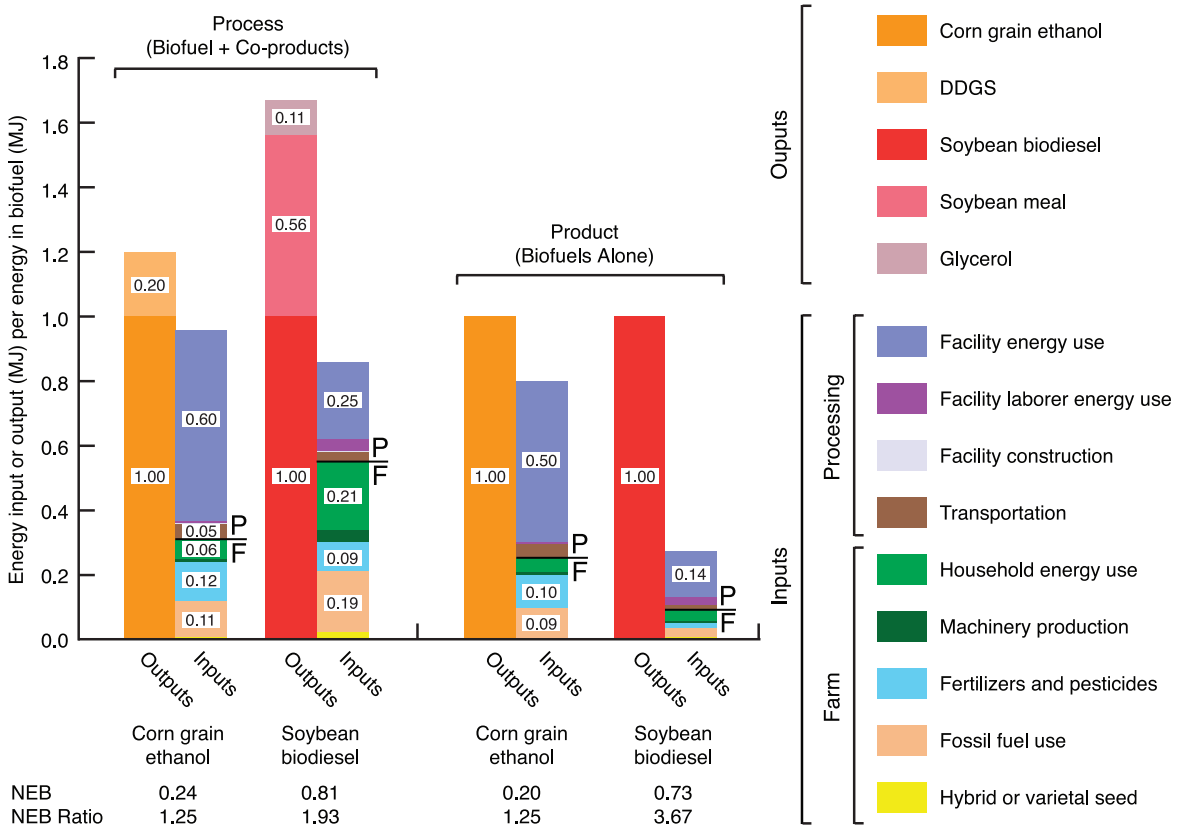

Fig. 1. NEB of corn grain ethanol and soybean biodiesel production. Energy inputs and outputs are expressed per unit energy of the biofuel. All nine input categories are consistently ordered in each set of inputs, as in the legend, but some are so small as to be nearly imperceptible. Individual inputs and outputs of ≥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 ≤ 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.

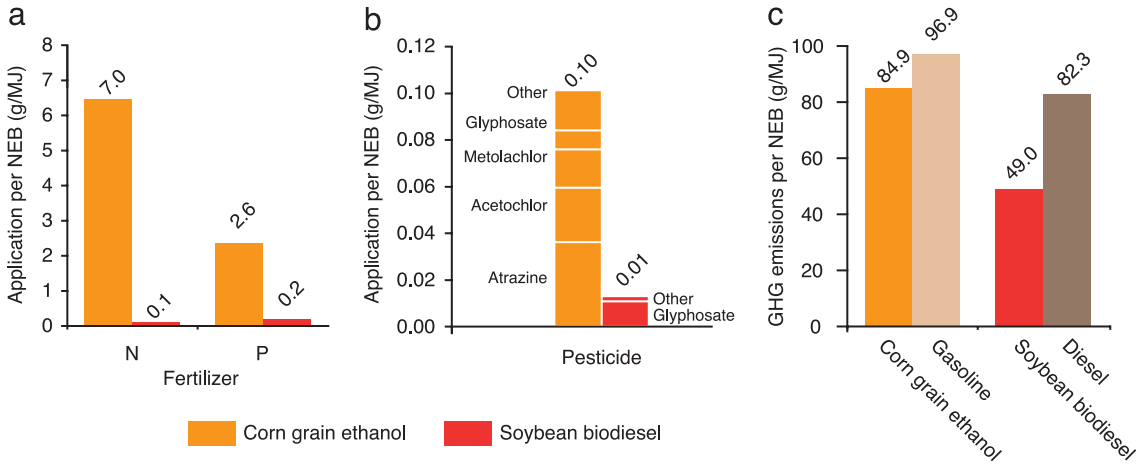

Fig. 2. Environmental effects from the complete production and combustion life cycles of corn grain ethanol and soybean biodiesel. (*a* and *b*) Use of fertilizers (*a*) and pesticides (*b*) per unit of net energy gained from biofuel production (Table 10). (*c*) Net GHG emissions (as CO_2 equivalents)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

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