



Environmental Trade-offs *of* BIOBASED PRODUCTION

Life-cycle analyses are needed to evaluate the potential benefits and consequences of bioproducts as petroleum substitutes.

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Potential reductions in greenhouse-gas (GHG) emissions and decreased dependence on foreign oil are fueling interest in the development of biobased products. Bioproducts represent a small but increasing market as petroleum substitutes. In 2006, U.S. production of ethanol and biodiesel was 4.9 billion gal and 90 million gal, respectively. Currently, 14% of the U.S. corn crop is consumed for production of ethanol (1), which is predominantly used as an oxygenate in gasoline. Table 1 shows the maturity of several biobased commodity technologies. Additional new products are developing rapidly.

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Biobased products are commonly thought of as environmentally preferable to petroleum alternatives because they are derived from renewable materials; however, the environmental profile of a product cannot be determined by a single metric, such as renewability. Historically, such unexamined assumptions have led to unintended and often undesirable consequences (for example, see box on p 5179). A holistic approach must be taken that examines the environmental impacts throughout a product's entire life cycle. By critically examining biobased systems and understanding the societal and environmental implications associated with large-scale bioproduct substitution, it may be possible to avoid or anticipate potentially detrimental effects and determine appropriate management strategies and policy initiatives.

A life-cycle analysis (LCA) of bioproduction systems is needed to evaluate potential benefits and consequences. LCAs document the material and energy flows and subsequent environmental impacts during feedstock production, processing, and use, and at end of life. With a few notable exceptions (2–4), LCAs conducted on bioproducts have focused on the climate-change benefits of biobased materials, often neglecting thorough analysis and quantification of impacts resulting from agriculture.

LCA studies have shown that biobased products have lower fossil-fuel consumption and GHG emissions compared with petroleum products (5, 6);

however, modern agricultural systems are responsible for significant environmental impacts because of reliance on fossil fuels, fertilizers, and agricultural chemicals. Disturbances in the nitrogen cycle in particular suggest the need for critical examination of the trade-offs associated with increased bioproduction. Despite their importance, nonpoint sources of nitrogen are generally not quantified in bioproduct LCAs because of large data variability and uncertainty (7). In a 2005 report, a survey of 20 bioproduct LCAs indicated that although every study included GHG emissions or fossil-fuel consumption, only five studies quantified nitrogen emissions (8). Agriculture's impacts on land use, ecosystem quality, and water consumption were similarly overlooked.

Although biobased production may be a preferred policy alternative to reduce petroleum dependence, its impacts must be understood and evaluated to minimize adverse consequences. This article examines the inherent trade-offs of carbon and nitrogen cycles related to agriculture. Comparison of carbon and nitrogen cycles is a key issue that should not be ignored. Toxic effects from pesticides, disruptions in the phosphorus cycle, land use, and socioeconomic concerns brought on by rising food prices are also major considerations (9).

Disruption of carbon and nitrogen cycles

Fossil-fuel combustion is the primary cause of global climate change, by releasing carbon sequestered be-

TABLE 1

Current status of the development of biobased products

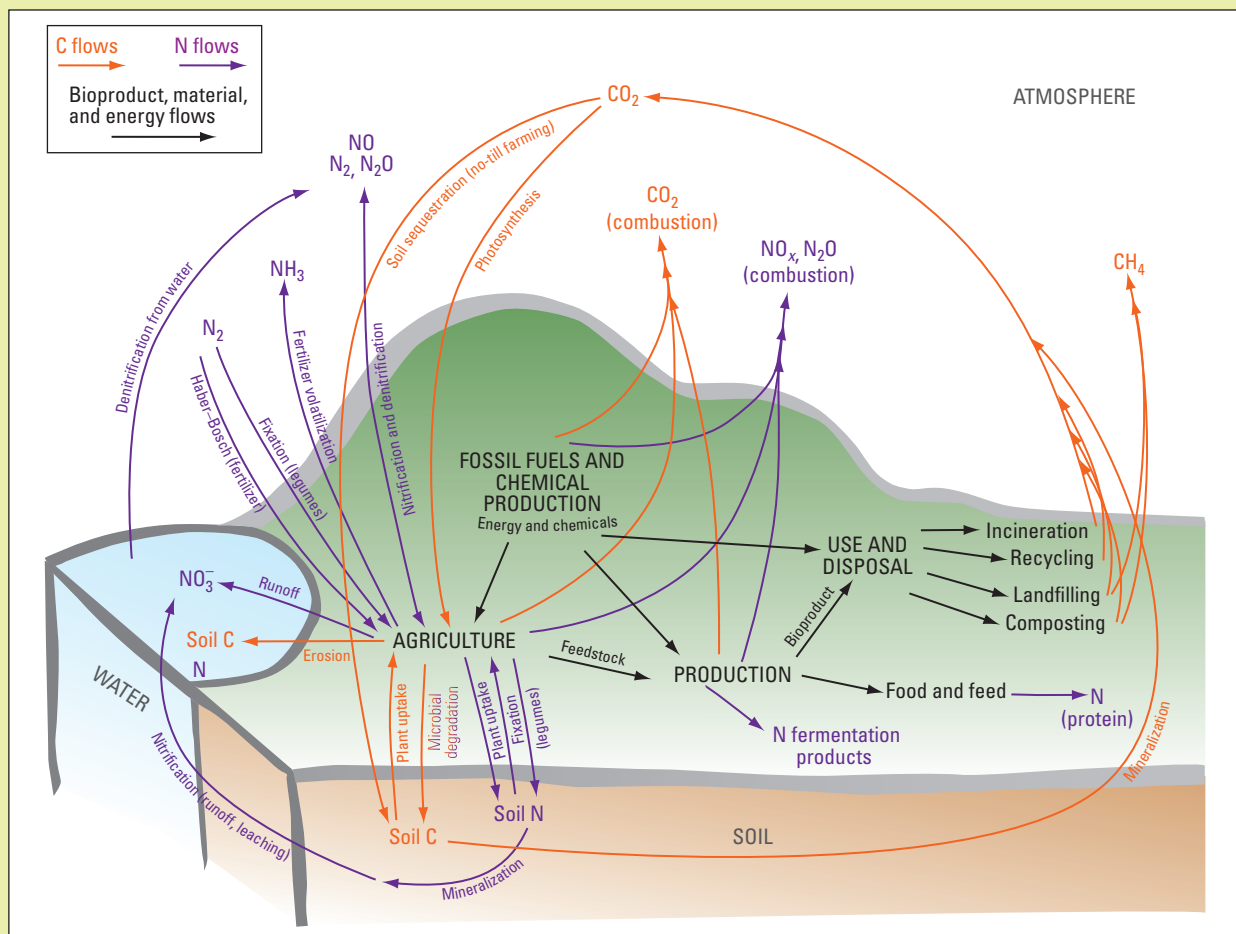
	Corn	Soy-beans	Sugar-cane, sugar beets	Cellulosic material (perennial grass, crop residue)	Starchy crops	Seeds (sunflower, rape, safflower)	New crops (kenaf, cuphea, milkweed, sorghum)	Algae	Food wastes	Animal by-products (manure, tallow, cheese, whey)
Energy										
Ethanol	●		●	▲	▲		▲		▲	
Biodiesel		●						▲	▲	
Other (e.g., gaseous, H ₂ , direct combustion)	▲	▲	▲	▲	▲		■	■	■	▲ ●
Materials										
Aggregates for construction materials				▲		■	■			
Solvents/inks/paints		●				■				
Plastics/polymers	●				▲				▲	
Lubricants		●				●		▲		▲
Specialty chemicals		▲		■	▲		▲	■		▲

● Currently in production.
▲ Active research area.
■ Potential exists for further development.

FIGURE 1

Relevant carbon and nitrogen fluxes for bioproducts

After being absorbed by plants during photosynthesis, carbon is rereleased at the end of the product's life via either combustion or biological processes. Reactive nitrogen, introduced either synthetically or via biological processes, is released throughout the life cycle, causing an increase in the aggregate nitrogen flux.



neath the earth's surface (10). In contrast, the combustion of biobased products is often referred to as a "carbon-neutral" system. Carbon released at the end of a bioproduct's life has been obtained from the atmosphere via photosynthesis and can be recycled to create additional biomass. Most bioproducts are not actually carbon-neutral, however, because carbon is emitted during fossil-fuel combustion throughout agricultural and biocommodity processing operations. Even so, adoption of biobased substitutes significantly reduces GHG emissions compared with petroleum counterparts. Therefore, the use of biobased products appears to be a logical step in climate-change mitigation (11).

The carbon and nitrogen cycles in agriculture are inextricably linked. Figure 1 depicts the relevant carbon and nitrogen fluxes pertaining to the life cycle of generic biobased products. As plants take up CO_2 during photosynthesis, a corresponding amount of nitrogen must be supplied to support plant development. The elemental ratio of carbon to nitrogen varies greatly according to the organism. Low C:N ratios have greater nitrogen requirements, which

must be obtained via natural processes or application of synthetic fertilizer. Sample biomass C:N ratios are listed in the supporting information.

Biobased production has carbon benefits; however, agriculture's contribution to reactive nitrogen flux is associated with many deleterious environmental consequences. Whereas fossil-fuel combustion is primarily responsible for the increase in CO_2 emissions, agricultural activities generate >75% of emitted reactive nitrogen compounds (12). Global atmospheric CO_2 concentrations have increased by about one-third since 1750; during the same period, a 15% increase in atmospheric N_2O concentrations has occurred; each molecule of N_2O represents a global-warming potential >300 \times that of CO_2 (10, 13, 14). Anthropogenic disruptions in the nitrogen cycle have led to a 1100% increase in the flux of nonreactive atmospheric nitrogen (N_2) to reactive nitrogen compounds (10, 13). Once converted to a reactive state, nitrogen persists in the environment, "cascading" through various compounds (NH_3 , N_2O , NO_x , NO_3^-), resulting in impacts such as the production of ground-level ozone, acidification, eutrophication,

hypoxia, stratospheric ozone depletion, and climate change (15).

Atmospheric nitrogen is converted to a reactive form by natural processes, such as biological nitrogen fixation (BNF) and lightning, and anthropogenically via manufacture of synthetic fertilizer. BNF occurs in the presence of select plant species that host microorganisms able to convert N_2 to a reactive form. Cultivated crops that fix nitrogen include soybeans, rice, alfalfa, and most legumes. Although BNF occurs naturally, intense cultivation of soybeans and rice has greatly increased the magnitude of nitrogen fixation.

For modern agricultural practices, native nitrogen stocks in the soil are insufficient to supply enough nutrients to sustain non-nitrogen-fixing row crops, such as corn. The indigenous supply must be augmented with additional nutrients—generally in the form of synthetic fertilizer, although animal manures are also used. Synthetic fertilizer is made through the energy-intensive Haber–Bosch process, which converts N_2 to ammonia. Production of synthetic fertilizer is estimated to be responsible for 1% of global primary energy consumption (16).

The carbon profile

The carbon profiles for different biobased products vary according to the amount of fossil fuel consumed throughout the agricultural and production processes, the amount of potential carbon sequestration, and the end of life of the bioproduct.

The GHG profile of a biocommodity depends upon whether it is burned, landfilled, biodegraded, recycled, or reused. For biomass converted into durable goods, the embodied carbon is not rereleased to the environment and may remain in a stable solid form indefinitely, resulting in net carbon sequestration. For combustible and biodegradable biobased products, net carbon sequestration doesn't occur, because the carbon taken up by plants is rereleased at the end of life. In general, products that are not combusted at the end of life and do not readily biodegrade will result in a greater carbon benefit. Although improved biodegradability is often advocated as an environmentally favorable trait, non-biodegradable bioproducts offer significant benefits from a climate-change perspective.

The end of life also dictates the form of carbon that is released to the environment. In combustion processes, the end product is primarily CO_2 . For biodegradation that occurs in anaerobic environments such as landfills, a significant fraction of the evolved carbon is methane, a 21× more potent GHG than CO_2 . If collected, methane can be burned for energy and oxidized to CO_2 (14). In the case of solvents and lubricants, carbon may be released as a volatile organic compound, which contributes to ground-level ozone formation and harmful human-health effects.

Research suggests that carbon sequestration benefits can be achieved by increasing the soil organic matter (SOM) in agricultural soils (17). When soils are tilled, exposure to air causes the SOM to oxidize and be released as CO_2 . This process also

slowly depletes the SOM in the system. Use of no-till practices allows organic matter from crop residues to replenish the SOM, sequestering carbon and increasing soil fertility. Carbon sequestration benefits are greatest for agricultural systems that are converted from high-intensity to no-till practices, and only accrue for the period of time required to replenish depleted SOM (18). In ~23% of planted area in the U.S., no-till practices are used; these achieve the most carbon sequestration benefits (19). Although no-till systems reduce erosion effects and increase SOM, no conclusive data exist on the effect of tillage practices on nitrogen emissions (20, 21).

Compared with petroleum products, bioproducts are primarily advantageous because of fossil-fuel avoidance—the relative amount of net carbon released is much smaller for bioproducts, reducing the net carbon flux (22). Soil sequestration effects are generally regarded as negligible when compared with petroleum avoidance because soil sequestration is practice-dependent and temporary, whereas the benefits from fossil-fuel avoidance are continuous and cumulative (22).

Unintended consequences

Unexpected consequences generally result from neglecting to examine all facets of a problem or a proposed solution. Solutions to one problem may create unanticipated consequences of a different nature.

One recent example is the use of methyl-*tert*-butyl ether (MTBE) as an oxygenate to reduce vehicular emissions. Although the additive allows more complete combustion of fuel, it also poses potential water-contamination risk because it enters groundwater more easily than other gasoline components after a leak or a spill. MTBE was originally chosen for its relatively low cost compared with other alternatives, but current estimates for MTBE remediation efforts range from \$1 billion to \$3 billion (30). Another example is the unanticipated adverse consequences of spills of ethanol–gasoline mixtures. The greater biodegradability and cosolvent effect of ethanol, originally presumed to be preferable to MTBE as an oxygenate, allow higher and more persistent concentrations of monoaromatic hydrocarbons (benzene, toluene, ethylbenzene, and xylene) in contaminated groundwater (31). Unintended consequences result not only at the end of life. For instance, electric vehicles touted as having “zero emissions” have significant environmental impacts due to upstream electricity generation (32).

The nitrogen profile

Nitrogen emissions from agriculture come from various sources. The largest source of nitrogen emissions by mass is nonpoint-source nitrate emissions, which contribute to eutrophication and hypoxia. Most NO_3^- emissions are generated after the harvest when no crops are available to absorb the available inorganic nitrogen pool. When introduced into nitrogen-limited watersheds, excess nitrogen causes increased algal activity, which depletes the water

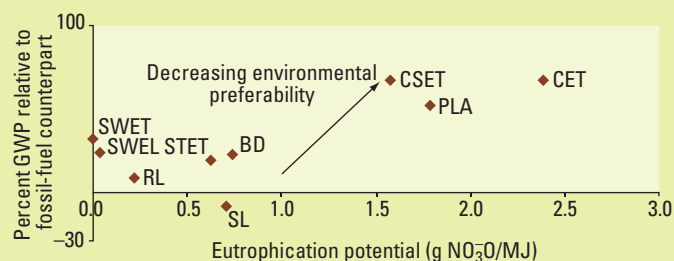
body of dissolved oxygen, creating an uninhabitable environment for fish and higher-level organisms. Hypoxia is one of the critical environmental issues facing coastal areas worldwide. Large hypoxic zones exist throughout the world, including the Gulf of Mexico, the Chesapeake Bay, Long Island Sound, the Baltic Sea, and the Black Sea, and such zones are increasing globally in both number and severity (15, 23)

In addition to posing regional water-quality problems, elevated nutrient loads can contribute to GHG emissions. When NO_3^- emissions are denitrified to N_2 , small fractions of NO and N_2O are produced as intermediates (24, 25). Riparian wetland buffers have been advocated to reduce adverse effects of nutrient loading; however, large nitrate loads introduced into these systems can lead to incomplete denitrification, increasing the fraction of N_2O and NO byproducts (24, 25). N_2O emissions resulting from denitrification of NO_3^- emissions are generally neglected in bioproduct inventories (25), although they are included in the Intergovernmental Panel on Climate Change (IPCC) guidelines (26).

FIGURE 2

Eutrophication potential vs relative global-warming potential (GWP) for various biobased products

Bioproducts increase in environmental preferability as relative GWP and eutrophication potential decrease. Bioproduct abbreviations (analogous fossil-fuel products are given in parentheses): BD, biodiesel (diesel); CET, corn ethanol (gasoline); CSET, corn and stover ethanol (gasoline); PLA, polylactic acid [from corn] (polystyrene [general]); RL, rapeseed lubricant (petroleum lubricant); SL, soybean lubricant (petroleum lubricant); STET, stover ethanol (gasoline); SWEL, switchgrass electricity (coal electricity); and SWET, switchgrass ethanol (gasoline).



As shown in Figure 1, reactive nitrogen compounds are also released directly from agricultural systems via fertilizer volatilization (NH_3) and nitrification/denitrification (NO_x , N_2O) reactions occurring in soils. Nitrogen compounds (NO_x , N_2O) are also generated from combustion processes associated with agricultural operations and processing of bioproducts (7).

In the U.S., the predominant cropping scheme rotates corn, which requires large amounts of fertilizer, with soybeans, which fix nitrogen. This practice reduces the amount of fertilizer needed by the agricultural system. Nitrate runoff is often assumed to be problematic only for crops receiving large amounts of fertilizer. Appreciable nitrate

runoff occurs even in systems receiving no fertilizer (27). For example, soybeans obtain a large portion of their nitrogen requirements through BNF, but they generate nitrate runoff during fallow periods. In corn–soybean rotations, the total amount of nitrogen in runoff can exceed the nitrogen applied to the field as fertilizer (27). Although soybeans emit smaller nitrate loads than corn on a per-area basis, nitrate emissions are greater on a harvested-mass basis (27 kg NO_3^-/t soy, 20 kg NO_3^-/t corn) because of lower crop yields (7).

Switchgrass and other perennial grasses have recently been proposed as potential energy crops. Switchgrass has not been widely cultivated as a harvested monoculture, and this has resulted in significant confusion about nitrogen requirements. Parrish and Fike (28) review the complicated nature of switchgrass nitrogen management, citing major disagreements regarding optimal nitrogen application. Recommendations range from zero to several hundred kilograms of nitrogen per hectare and often exceed the fertilizer recommendations for corn. These discrepancies exist because of the uncertainty surrounding switchgrass cultivated as a cash crop and the impact increased fertilizer will have on yields. Switchgrass has much greater yields than most row crops; this results in low nitrate emissions per mass of crop (0.01 kg NO_3^-/t switchgrass).

Trade-offs of carbon and nitrogen impacts

Climate change is an important and critical issue, but the environmental impacts resulting from emissions of reactive nitrogen are also significant. Biobased products are clearly an improvement over petroleum products with respect to climate change; however, agricultural systems are largely responsible for the increase in global fluxes of reactive nitrogen and declines in regional water quality. For future policy initiatives, it is important to determine the extent to which regional water quality is compromised to realize benefits from carbon emissions reduction. For bioproducts, fundamental trade-offs exist between global climate change and nitrogen-related impacts.

Figure 2 shows the trade-offs of improved climate-change potential and water-quality degradation resulting from bioproduct adoption. Representative life-cycle studies were collected to show the impacts of bioproduct adoption. The data used to construct the figure are contained within the supporting information. Although the products presented in Figure 2 have different functions, they are compared on an energetic basis in order to use a similar metric for comparing nitrogen intensity. These data are presented with the understanding that significant variability and uncertainty exists and that specific values may change somewhat because of differences in boundary assumptions.

Figure 2 shows the increase in eutrophication potential associated with bioproduct adoption versus the amount of climate-change benefit. Lower values indicate the smallest environmental impact. Positive values on the y axis indicate net positive carbon emissions, whereas 0% is the equivalent of

a carbon-neutral bioproduct. A negative value represents net carbon sequestration, which can only be obtained by durable bioproducts. A value >100% indicates a GWP greater than that of the fossil-fuel alternative.

Figure 2 indicates that not all bioproducts have similar environmental profiles. Each bioproduct achieves lower GWPs relative to petroleum products but increased eutrophication impacts. The most favorable bioproducts are found in the lower left corner. Products farthest from the origin offer few climate-change benefits and introduce significant eutrophication potential.



Although all bioproducts have increased eutrophication potentials, some do not offer significant climate-change benefit. For instance, corn-based ethanol does not offer much reduction in GWP relative to gasoline yet has the greatest eutrophication impact of the bioproducts surveyed. Conversely, switchgrass-based ethanol offers good climate-change benefits as well as a low eutrophication impact due to high yields per acre. Moreover, the three bioproducts with the least preferable C:N profiles are corn-based ethanol, combined corn and stover ethanol, and corn-based polylactic acid. This is significant given the current focus on corn-based bioproduction, and suggests that alternative biomass feedstocks may be preferable.

The U.S. subsidizes 40 million acres of agricultural land currently not in production. If this land is dedicated to the production of biomass for commodity goods in the future, the environmental consequences from nitrogen have the potential to become more severe. Proactive environmental management techniques are needed to insure against undesired outcomes. A need exists for greater incentives to improve the nitrogen efficiency of crops and to mitigate the impacts of excessive nitrogen loads. The nitrogen emissions from agriculture do not necessarily imply that biobased products are not or cannot be environmentally preferable. Numerous best management practices, which are well docu-

mented, can lessen the environmental impacts of modern agriculture from both carbon and nitrogen perspectives (29). Mitigation of excess nitrogen can be realized by changing the nitrogen management strategy, improving nitrogen application efficiency, planting winter crops or perennials to reduce runoff, or implementing wetland buffers. The carbon profile of bioproducts can be improved even further by reducing energy use throughout the life cycle and converting more farms to no-till practices. In addition, products and feedstocks that have lower aggregate impacts can be promoted preferentially to those with moderate climate-change benefits and greater eutrophication potential.

The case of bioproduction shows that no perfect alternatives for improved environmental performance exist. The trade-offs involved in bioproduction emphasize the need to analyze problems in a systematic and holistic manner. Once trade-offs are recognized, improved tools must be developed to enable informed decisions.

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Supporting information

Supporting information, including a discussion of C:N ratios and a table of values for several biomass feedstocks as well as source material and a description of calculations used to derive Figure 2, is available at <http://pubs.acs.org/est>.

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