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SUMMARY

Biofuels, liquid fuels derived from biological materials such as crop plants, forest products, or waste materials, have been widely promoted as a means to reduce dependence of our transportation systems on fossil fuels and to reduce emissions of the greenhouse gases (GHG) that contribute to global warming. The primary forms of biofuels are ethanol, made from sugars, starches, cellulose, and other plant structural components, and biodiesel, made from oils produced by plants. Many countries, including the United States and members of the European Union, have adopted production and use targets for biofuels. The promise of biofuels as a renewable, environmentally friendly energy source, combined with these mandates, has driven a worldwide expansion in their production. However, many questions remain about how to produce biofuels without causing new and unanticipated environmental impacts. In this report we summarize the environmental effects of biofuels, illustrate some uncertainties about these effects, and identify topics for an integrated research program aimed at clarifying tradeoffs and reducing uncertainties in planning for sustainable biofuels production. Our considerations include effects on GHG emissions, soil carbon, water supply and quantity, land use, and biodiversity.

We conclude:

- Estimated net GHG emissions from biofuels production can be lower than those of fossil fuels. However, this is highly dependent on feedstock (raw material) choice, fuel and fertilizer inputs, whether biofuel crops replace native vegetation, and whether the soil is tilled. Further, emissions estimates for a given feedstock vary among studies, contributing to uncertainty about GHG effects.
- The effects of biofuels production on water supply and quality are a function of the feedstock choice and production method. High intensity agricultural crops such as fertilized and irrigated corn can contribute nitrogen and phosphorus pollution to adjacent waterways and downstream, and can place substantial demands on regional water supplies. Perennial cellulosic crops such as switchgrass and mixed prairie grasses can substantially reduce these impacts.
- Today's grain-based biofuel crops compete with food crops for prime agricultural land. Pressure is growing to expand grain-based biofuels production onto marginal agricultural lands or land currently in the U.S. Department of Agriculture (USDA) Conservation Reserve Program. These lands support diverse wildlife communities and conversion is likely to affect some species of concern. Land conversion is also a major source of GHG production, especially when native habitats are destroyed. Land use impacts can be reduced by selecting feedstocks that do not displace food crops or require conversion of native habitats for production.
- Impacts on wildlife abundance and diversity depend on the feedstock choice and whether production takes place on existing agricultural lands or on newly cleared land. At a landscape scale, more diverse feedstock crops are associated with greater biological diversity, while monocultures decrease it. Some plants being considered as sources of biofuels are potentially invasive, requiring consideration of potential impacts on habitats adjacent to the biofuels crop.

Biofuels production presents a wide range of potential impacts and benefits, with substantial uncertainty associated with different choices among sources and production methods. Society must carefully consider the environmental tradeoffs of different biofuels sources, and of biofuels compared with other energy sources, including fossil fuels. An integrated research program that explores optimal crop selection, agricultural landscape design, effects on GHG emissions, soils, and biodiversity, and economic and social factors, is necessary to fully inform decisions about these tradeoffs. Appropriately designed, a biofuels production system can be a sustainable and resilient source of energy for the long term.

Cover photos: *Examples of biofuel feedstocks. Clockwise starting on the upper left: (a) Switchgrass (*Panicum virgatum*), a prairie grass native to North America (b) Two species of algae (*Cyclotella and Oocystis*) (c) Sunflowers (d) Hybrid poplars (crosses between two or more species of *Populus*), (e) Corn field.*

Photos credits: *(a) Peggy Greb, USDA-ARS (b) Robert O. Megard, University of Minnesota (c) Edward McCain, USDA-ARS (d) Stephen Ausmus, USDA-ARS (e) Flickr user fishhawk.*

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Introduction

Policy makers are increasingly looking to renewable energy sources as environmentally friendly and sustainable replacements for fossil fuels used for transportation. Biofuels, which are liquid fuels derived from a variety of sources—for example, row crops, trees, algae, and food waste— appear to hold promise to reduce our dependence on fossil fuels and to reduce net emissions of greenhouse gases (GHG) from mobile sources that contribute to global warming. Many countries, including the United States, have set targets for biofuels production (ethanol and biodiesel) and mandated the blending of ethanol with gasoline. These policies, combined with economic incentives and tariffs, have driven a worldwide expansion in the production of various crops for use as transport fuels. At present, biofuels are primarily derived from a small number of plant materials, or feedstocks, primarily corn and sugar cane, but the variety of materials is expanding.

Worldwide biofuel use for transport is expected to nearly double by 2017 over 2005–2007 levels.[1] A target adopted by the European Union (EU) in 2009 requires 10% of fuels for transport to be from renewable sources by 2020. In the U.S., ethanol, which accounts for more than 99% of biofuels produced, is made almost exclusively from corn grown on prime agricultural land. With rising demand and legislative targets for biofuels, increasing output will require boosting yields of existing crops, bringing more land into biofuel crop production, and/or developing new feedstocks (see Box 1).

Provisions in U.S. legislation, including the U.S. Energy Independence and Security Act of 2007 and the Food, Conservation and Energy Act of 2008 (known as the Farm Bill), set new targets and incentives for biofuels production. In amending an earlier Renewable Fuel Standard (RFS), the Energy Independence and Security Act called for a nine-fold increase in renewable fuel production by 2022. Gasoline for road transportation would have to consist of 20% biofuels by this date. The U.S. Environmental Protection Agency (EPA) in 2010 issued new production targets for various biofuels and detailed schedules for meeting them (see Box 2.) The 2008 Farm Bill increased targets in the U.S. and established tax credits, grants, and other provisions to encourage the expansion and use of transport biofuels, with new emphasis on fuels derived from cellulosic sources.

If produced in a sustainable fashion, biofuels could reduce demand for fossil fuels, in turn reducing needs for imported oil and mitigating climate change by limiting GHG emissions. As with any agricultural crop, however, biofuel crops can affect water supply and quality, soil biogeochemistry, land use, and biodiversity. Erosion, nutrient runoff, habitat loss, the loss of beneficial species, and the spread of invasive species are all potential risks of expanded production. Scientists and policy makers are examining how potential adverse effects on natural resources can be avoided or mitigated in order to meet biofuels production goals while enhancing environmental, social, and economic sustainability.

Research has also focused on the impacts of various economic policies intended to stimulate biofuels production, the economics of growing crops for transportation fuel, and the potential impact on worldwide food production. As the need for food increases with a burgeoning global human population, biofuel crops compete for arable land and may lead to higher food prices. While acknowledging the potential economic and social implications, the objectives of this report are to summarize the environmental effects of biofuels, illustrate some of the uncertainties about those effects, and identify topics for an integrated research program that could reduce uncertainties in planning for sustainable biofuels production. We first summarize the potential direct and indirect effects of biofuels production on GHG emissions and soil carbon. Subsequent sections describe impacts on water use and quality, biodiversity, including the effects of land conversion, monoculture agriculture, invasive species, and the potential tradeoffs between biofuel energy yield and biodiversity. We propose elements of an integrated research program that could reduce the identified uncertainties. Finally, we link a set of princi-

Box 1. Types of Biofuels and the World's Major Producers

Biofuels are a renewable energy source derived from biological materials such as crops, wood, or algae grown specifically for fuel purposes or from wastes such as forest or agricultural residues and municipal waste. Biofuels come in two primary forms: ethanol and biodiesel. Ethanol, the most widely used renewable transportation fuel, is an alcohol fuel made from sugars found in grains or derived from starches, cellulose, and other plant components. Virtually all of the transportation biofuel produced in the U.S. today is ethanol derived from corn grain. The U.S. also imports ethanol, largely sugarcane-based ethanol from Brazil, which together with the U.S. supplies 90% of the world's fuel ethanol.[a] Owing to increased domestic production and tariffs on imported ethanol, imports have declined in recent years.[b] Ethanol is generally blended with gasoline, although some cars can run on pure ethanol. In 2009, ethanol made up about eight percent of the U.S. motor vehicle gasoline market, which is nearly double the market in 2006. A wide variety of perennial grasses, including both native prairie species such as switchgrass and exotic species such as miscanthus, are being studied for their potential as biofuel crops. Because cellulosic ethanol can be made from any number of plant species, including trees, mixtures of species can potentially be grown to optimize environmental benefits in addition to fuel production. Such mixtures might comprise two to three species of native grasses and forbs grown together to enhance prairie restoration. Cellulosic biofuels constitute less than a half-percent of current biofuels production in the U.S., although this proportion is expected to grow rapidly, in part due to incentives for development that acknowledge their superior environmental benefits.

Biodiesel, now made largely from palm and vegetable oils, fats, or greases, can be blended with diesel fuel or used directly in diesel engines. Biodiesel is currently produced largely in the EU and particularly in Germany, although biodiesel production is expanding worldwide, particularly in Southeast Asia, the U.S., and parts of South America and Europe. Biodiesel from the EU is made primarily from canola (also known as rapeseed), although the U.S. and Brazil, among others, have also used soybeans for biodiesel. Oil palm plantations have expanded in Southeast Asia for production for biodiesel (see Table 1).

Algae constitute another potential biofuel feedstock. Algae grown in outdoor ponds or enclosed in containers ("photobioreactors") are typically harvested, dewatered, and dried for their lipids and oils, which can be used to make biodiesel, ethanol, or other hydrocarbons. Some producers are developing systems in which the algae excrete the desired product, for example ethanol, into the culture medium and the product is then extracted from the medium without the need for harvesting of the algae.

[a] World Bank. 2008. Biofuels: the promise and the risks, in World Development Report 2008. http://siteresources.worldbank.org/INTWDR2008/Resources/2795087-1192112387976/WDR08_05_Focus_B.pdf

[b] Renewable Fuels Association. 2012. www.ethanolrfa.org/pages/statistics viewed 7 December 2012.

Figure 1. Examples of different biofuel types. a) field corn (conventional bioethanol); b) switchgrass (advanced bioethanol); c) sunflower (conventional biodiesel); d) green alga Botryococcus braunii *(advanced biodiesel, bioethanol, biobutanol, aviation fuels). Photo credits: a) Warren Gretz / NREL b) Bob Nichols / USDA c) Peggy Greb / USDA. d) Tim Devarenne / Texas AgriLife Research.*

Table 1. Major biofuels and their sources. "Conventional" biofuels are those that dominate today's marketplace. "Advanced" biofuels are new-generation fuels under experimental production.

Type of Biofuel	Feedstock	Where produced
Conventional bioethanol	Corn	United States, Canada
	Sugarcane	South America (primarily Brazil), Central America, Asia, Africa
	Sugar beets	Europe
	Cereals (e.g. milo, wheat, barley)	Europe, Canada
	Cassava	Asia, South and Central America
Advanced bioethanol	Cellulosic biomass • Grass (e.g. switchgrass, miscanthus, mixed species) • Short-rotation woody crops (e.g. poplar) • Plant waste (e.g. corn stover, wood waste)	In development
Conventional biodiesel	Rapeseed (canola)	Europe, Canada, Asia
	Soybean	Europe, Canada, South and Central America, Africa, Asia, United States
	Sunflower	Europe, Canada, Africa, Asia
	Palm	South and Central America, Africa, Asia
	Jatropha	South and Central America, Africa, Asia
	Castor	South and Central America
Advanced biodiesel, bioethanol, biobutanol, aviation fuels	Algae	In development

Source: United Nations Environment Programme. 2009. Towards sustainable production and use of resources: assessing biofuels. http://www.unep.org/PDF/Assessing_Biofuels.pdf ples for biofuels and sustainability to a landscape approach designed to meet social, economic, and energy needs.

Potential Environmental Effects

The potential environmental effects of biofuels production have been examined using field measurements, laboratory experiments, computer models, and combinations of two or more of these methods. Not all studies agree with each other, and we discuss some of the reasons for differing conclusions. The effects of biofuels on the environment are many and complex; they vary greatly depending on initial conditions and assumptions.

Greenhouse Gas Emissions and Soil Carbon

GHG emissions resulting from biofuel production depend on 1) land clearing, if necessary, and whether the feedstock crop replaces native vegetation or another existing crop; 2) feedstock choice; 3) fuel and energy use for crop growth, harvest, and biofuels production; 4) water use and source; 5) the use of nitrogen fertilizers; and 6) soil turnover effects on carbon and nitrogen emissions (Box 3). The use of fossil fuels and nitrogen fertilizer has direct effects on emissions. Indirect effects can occur when biofuels production displaces another agricultural activity (e.g., cattle grazing in tropical regions which then expands into native rainforest). Whether biofuels production causes net GHG emissions, has no net GHG emissions, or takes up GHGs from the atmosphere (e.g., by storing carbon in plant roots and soil) depends on the entire life cycle of production and use. For this reason, researchers studying the effects of biofuels production on GHG emissions generally conduct life cycle analyses (or assessments), known as LCAs (Box 4). An LCA describes the impacts of a product at every step from start to finish—

Terms and Definitions

biofuels	Liquid fuels derived from biological materials such as crop plants, forest products, or waste materials
carbon debt	The amount of carbon released as a result of land use conversion, for example from grassland or forest to crops for biofuels production. The carbon debt can be repaid over time if the biofuel produced has lower greenhouse gas emissions than the fossil fuel that it replaces (see reference 8).
cellulosic	Refers to fuel derived from vegetative plant tissue, composed primarily of cellulose, hemicellulose, and lignin (for example, crop residues, wood, and grass not harvested for grain); contrast to grain-based or algae-based biofuels.
CO_2	Carbon dioxide
CRP	Conservation Reserve Program of the U.S. Department of Agriculture
EPA	United States Environmental Protection Agency
EU	European Union
feedstock	The source material for biofuel, for example, algae, crop plants, waste materials, or wood
foregone sequestration	The carbon that would otherwise have been stored by an ecosystem in the absence of its conversion to biofuel cropping
GHG	Greenhouse gas
hypoxia	Oxygen deficiency
indirect land use change	Refers to the carbon cost of converting grassland or forest to food crops in order to replace the food production lost when cropland elsewhere is diverted to biofuels production
no-till	Farming without plowing (tillage); the prior crop's residue is left on the soil surface to decompose.
N_2O	Nitrous oxide
RFS	Renewable fuel standard. The first RFS was established by the U.S. Environmental Protection Agency under the Energy Policy Act of 2005. RFS2, an expanded version of the standard, was developed in response to the Energy Independence and Security Act of 2007.
stover	Corn leaves and stalks, a potential cellulosic feedstock
USDA	United States Department of Agriculture

Box 2. Types of Biofuels Defined by EPA

For regulatory purposes, the U.S. Environmental Protection Agency defines biofuels. Fuels developed to meet U.S. production targets must meet the requirements of those definitions.

Renewable fuel: Fuel produced from renewable biomass and that is used to replace or reduce the quantity of fossil fuel present in a transportation fuel. It must also achieve a life cycle GHG emission reduction of at least 20%, compared to the gasoline or diesel fuel it displaces. [Ethanol derived from corn grain currently would fall in this category.]

Target: Total of 36 billion gallons by 2022 (minimum of 15 Bgal additional).

Advanced biofuel: Renewable fuel other than ethanol derived from corn starch, with life cycle GHG emissions at least 50% less than the gasoline or diesel fuel it displaces. Includes sugarcane ethanol, cellulosic ethanol, and algal biodiesel, for example.

Target: Total of 21 billion gallons by 2022 (minimum of 4 Bgal additional).

Cellulosic biofuel: Renewable fuel derived from any cellulose, hemicellulose, or lignin (components of stems, stalks, and woody parts of plants) each of which must originate from renewable biomass. It must also achieve a life cycle GHG emission reduction of at least 60%, compared to the gasoline or diesel fuel it displaces. Cellulosic biofuel generally also qualifies as both “advanced biofuel” and “renewable” fuel.

Target: 16 billion gallons by 2022.

Biomass-based diesel: Any diesel fuel made from renewable biomass feedstocks or from vegetable oils or animal fats. Its life cycle GHG emissions must be at least 50% less than the diesel fuel it displaces, and it cannot be co-processed with a petroleum feedstock.

Target: 1 billion gallons by 2012 and beyond.

in the case of biofuels, from field to tailpipe. Results of LCAs depend partly on the spatial and temporal boundaries of the analysis, for example on the inclusion (or not) of factors such as the GHG emissions resulting from the construction and operation of the biofuel refinery. Conclusions of different studies therefore vary depending on the boundaries selected and the models used. The studies summarized below are based primarily on LCAs.

Direct Effects

A growing body of environmental evidence on GHG production has dampened enthusiasm for corn as a feedstock. This is due in part to the way corn is cultivated and in part to the biology of the plant itself. Corn, like many other annual crops, depends on fossil-fuel inputs for planting, harvesting, and ethanol production. Moreover, a major factor in the GHG balance of biofuel systems is how much carbon remains stored in the soil. Soil organic carbon is also necessary to maintain soil productivity. Conventional farming practices for annual crops involve tilling the soil, which substantially reduces soil organic carbon from pre-conversion levels. When the soil is tilled, microbes are stimulated to release more stored carbon into the atmosphere as carbon dioxide (CO_2). According to the U.S. Economic Research Service, about 70% of the land dedicated to corn is currently tilled. Growing corn without tillage (no-till), alternatively, conserves soil carbon. Crop residue (corn cobs and corn stover - the leaves and stalks), left on the field will also conserve soil carbon. Corn production requires high inputs of nitrogen fertilizer. High nitrogen fertilization can cause corn stover to degrade more readily to CO_2.[2]

A recent modeling study shows that when conservation reserve or native grassland is converted to corn production using conventional tillage, there are large losses of soil carbon. The use of no-till practices greatly reduces soil carbon loss. Other agricultural practices that can reduce GHG emissions from grassland conversion include the use of slow-release fertilizer and nitrification inhibitors that have the potential to reduce soil nitrous oxide (N_2O) fluxes by more than 50% (Box 3).

There are roughly similar N_2O emissions for corn and soybeans, and lower values for fertilized switchgrass, according to EPA. Estimates of GHG emissions of both corn ethanol and soybean biodiesel production are often only slightly lower, and sometimes higher[1], than petroleum, although some analyses suggest that best practices, if enacted, could provide GHG reductions relative to petroleum of up to 50%.

In contrast to grain cultivation, cellulosic feedstocks require fewer fertilizer inputs and, because they are perennial rather than annual plants, require no tilling. Consequently they store or “sequester” carbon in the soil. Perennial biofuel crops such as switchgrass or mixed prairie grasses actually can reduce

Box 3. Biofuels and Nitrous Oxide Emissions

In theory, biofuels should not contribute to GHG buildup in the atmosphere because the plants grown for fuel take up carbon dioxide (CO_2) as they grow, offsetting carbon released to the atmosphere when the fuels are burned. However, although CO_2 gets most of the attention, there is another GHG of serious concern (see Figure 2). Only about half of the nitrogen applied to a grain crop is taken up by plants while the remainder is lost to the environment. Some of the nitrogen ends up in the atmosphere as nitrous oxide (N_2O), a greenhouse gas 300 times more potent than CO_2. Most of the N_2O is lost from the field itself, but some is lost indirectly after nitrate leached from the fields is transformed to N_2O in downstream waterways and wetlands. Row crop agriculture is the largest human source of N_2O globally, and N_2O loss is often the biggest GHG source in annual cropping systems.

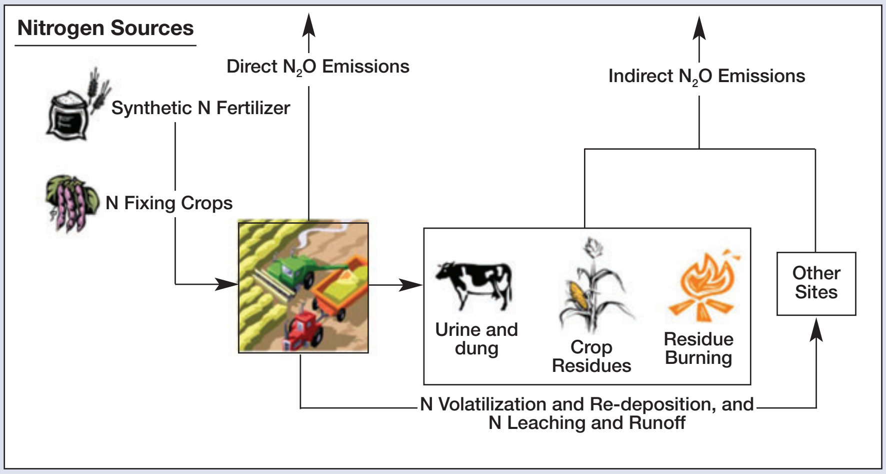

Figure 2. Nitrous oxide (N_2O) emissions from agriculture.

atmospheric GHG concentrations by transforming CO_2 in the atmosphere to stored soil organic carbon. Soil organic carbon increased in switchgrass fields harvested annually over a five-year period.[3] Similar carbon storage findings have also been reported for "low input, high diversity" vegetation.[4] These crops, which require little or no fertilizer input, stored more than 30 times as much carbon in soil and roots as monoculture soybean and corn crops. After accounting for the release of CO_2 from fossil fuel combustion during all phases of production and processing, the GHG emissions reduction attributable to low input high diversity biomass was 6 to 16 times greater than for corn or soybeans. An additional benefit to the GHG balance is that N_2O output by cellulosic crops can be half that for grain feedstocks.

Substantial increases in soil carbon sequestration could occur if the 30-40% of current U.S. lands used for corn were replaced with cellulosic perennial grasses, according to modeling studies. Miscanthus, a perennial grass native to Africa and Asia, for example, has high soil carbon storage, because it has a high rate of root biomass production and does not need much fertilizer. Projections for native North American switchgrass, on the other hand, are less optimistic. Growing switchgrass without fertilization significantly decreases soil carbon and nitrogen.

Algal biofuels production systems are in the early stages of development, and while a number of pilot scale production facilities are being constructed, it is difficult to make definitive statements about the GHG emissions of commercial-scale production systems. A comparison of the potential environmental impacts of algae with other biofuel feedstocks found that algae had much higher GHG emissions than corn, switchgrass, or rapeseed.[5] This is attributable to the use of petroleum-based fertilizers for algal culture and to energy required to produce the CO_2 that is bubbled into the water as a carbon source for the growing algae. The GHG balance might be improved by finding ways to recycle flue gas from fossil fueled power plants to provide CO_2 and wastewater from water treatment plants as a source of nitrogen and phosphorus for the algae. Co-location of algae production systems with power plants could also increase the overall energy produced per CO_2 from the combined power and fuel production. According to EPA, air pollutant emissions associated with algal biodiesel production are lower than those of other biodiesel feedstocks and much lower than emissions from corn ethanol production. Waste material from algal biofuels production could potentially be used as cattle or fish food, or further digested to make syngas or other biofuels. A National Research Council report, *Sustainable Development of Algal Biofuels in the United States*, addresses the sustainability of algal biofuels in detail.

Liquid fuels produced from forest products such as wood or other biomass residues may reduce net GHG emissions more than fuels produced from agricultural sources like fast-growing poplars or other short-rotation woody plants. GHG reductions reported for ethanol produced from woody biomass, compared with gasoline, range from 51% to 107%.[6] However, in order for wood harvested for biofuel to have no net carbon emissions, or net carbon storage, it must be grown and harvested in such a way that the landscape-level carbon captured equals or exceeds that which the forest would have stored without being used for biofuels.[7]

Indirect Effects

Plant biomass and soils store large amounts of carbon, so land conversion that destroys these stores and accelerates the decomposition of carbon creates a "carbon debt" by releasing CO_2 into the atmosphere. Converting unfarmed perennial vegetation to annual crops grown for biofuels loses not only much of the carbon currently in the soil but can also lose the future carbon that would have been stored if the land had been left unconverted. Repayment of this "carbon debt" can occur once the net GHG emissions from production and combustion of the biofuels drop below the GHG emissions of the fossil fuel being replaced. Conversion of native lands (tropical rainforest, peatland rainforest, native Brazilian grasslands, and grasslands in the U.S.) was estimated to incur large carbon debts that would take decades to centuries to pay off, depending on the crop and the type of land being converted.[8] Conversion of grasslands in the central U.S. to production of corn for ethanol would create a carbon debt that would take 93 years to repay. The estimated payback time for the carbon debt associated with converting Conservation Reserve Program (CRP) land in Michigan to biofuels under five different scenarios ranged from 29 years for corn-soybean rotations managed without tillage to

Box 4. What Is Life Cycle Analysis?

Life cycle analysis or assessment (LCA) provides a "cradle to grave" picture of all environmental impacts of biofuels and the processes that go into producing them. The U.S. Environmental Protection Agency[a] describes LCA as a systematic, phased approach with four components:

- *Goal definition and scoping* describes the product, process or activity; establishes the context for the assessment; and identifies the boundaries and environmental effects to be reviewed.
- *Inventory analysis* identifies and quantifies the energy, water, and materials use and environmental releases (e.g., air emissions, solid waste disposal, wastewater discharges).
- *Impact assessment* assesses the potential human and ecological effects of energy, water, and material use and the environmental releases identified in the inventory analysis.
- *Interpretation* evaluates the results of the inventory analysis and impact assessment.

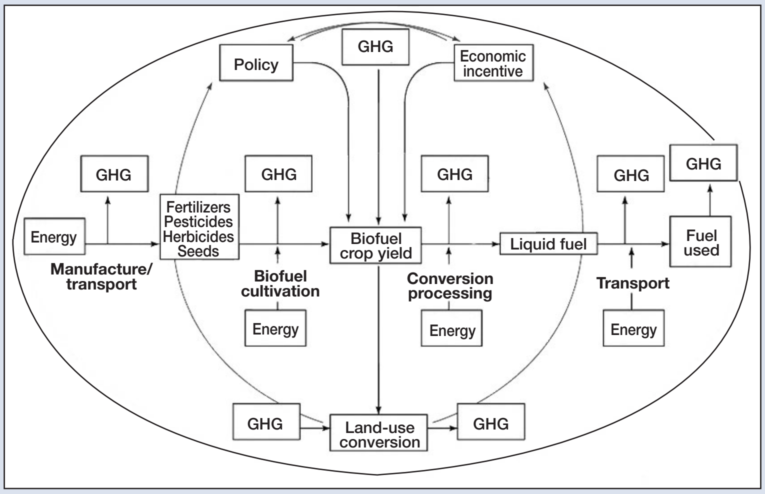

Figure 3. GHG life cycle analysis of biofuels. Adapted from SC Davis et al. *2009.* Trends in Plant Science *14: 140-146.*

An LCA incorporates data on many aspects of the life cycle, including fertilizer use, changes in crops or acreage, and energy used for growing and transporting feedstocks and for processing the biofuel. These data are then used in economic and environmental models to assess net effects on GHG generation (see Figure 3).

While an important tool, like any analysis LCA does not guarantee agreement among investigators. One reason for the variation in results is disagreement about what factors should go into an LCA. For example, one criticism of LCAs is that they often leave out various types of information, such as how changes in prices will affect other variables and feed back into the cycle. Such indirect effects are perhaps the most difficult to quantify and thus the most contentious.

LCAs are imperfect, but they are incorporated into legislation such as the Energy Independence and Security Act. EPA's RFS2 standard, for example, uses indirect land use analysis in determining the life cycle GHG emissions of various biofuels sources. As noted in the regulation, "Congress specified that: The term 'lifecycle greenhouse gas emissions' means the aggregate quantity of greenhouse gas emissions (including direct emissions and significant indirect emissions such as significant emissions from land use changes), as determined by the Administrator, related to the full fuel lifecycle . . ." (40 Code of Federal Regulations Part 80).

There are challenges for both scientists and policymakers when there are no accepted protocols or rules for deciding which components should be included or excluded in LCAs. Calls for standardized approaches for biofuels LCA thus seem particularly pertinent given the importance of these analyses for policy.[b]

Sources:

[a] U.S. Environmental Protection Agency. 2006. Life cycle assessment: principles and practice. EPA/600/R-06/060, USEPA, Cincinnati, OH.

[b] Mitchell, R.B., L.L. Wallace, W. Wilhelm, G. Varvel, and B. Wienhold. 2010. Grasslands, rangelands, and agricultural systems. Biofuels and Sustainability Reports, Ecological Society of America, Washington, D.C. http://esa.org/biofuelsreports/

123 years for continuous corn conventionally tilled.[9] In contrast, using CRP land directly for cellulosic biofuel incurred no debt, providing immediate GHG mitigation benefits.

In Brazil, where biofuels production is an important agricultural industry, land use change from rangeland to cropland is estimated to have a small impact on carbon emissions.[10] However, the indirect impacts could offset the carbon savings from biofuels if displaced ranches expand into the Amazonian rainforest, replacing native forests with pastures. A similar problem could occur where production of sugarcane has moved into areas where soybeans are currently grown; displacement of soybean farming may put further pressure on Amazonian forests.[11]

In the United States, where biofuels crops are more likely to be grown on land already in agricultural production, indirect land use change is still a risk. Global demand for the agricultural commodities that are displaced by new energy crops may lead to the expansion of agriculture in new and distant areas, with associated environmental and economic costs of land use change in those areas.[12] This is the argument of Searchinger and colleagues,[13] who predict that as prices for biofuels rise, farmers around the world will convert forest or grassland to make up for land or grain that has been diverted for biofuels. Using a worldwide agricultural model, they estimated the additional GHG emissions that would result from this change in land use. Production of corn-based ethanol, rather than reducing GHG emissions, would nearly double them over a 30-year period and increase them for 167 years. Biofuels produced from switchgrass, which as mentioned earlier is widely considered to be environmentally preferable to corn, could increase GHG emissions by 50% if grown on land used for food production.

However, some researchers argue that the effects predicted by Searchinger and colleagues depend on uncertain parameters, such as how prices drive changes in land use and ethanol consumption and production in the United States and Brazil.[14] Others believe these authors underestimated several important parameters: yields per acre of food in developing countries, the potential for raising those yields, the availability of high-yield cellulosic feedstocks in the U.S., and the global availability of unused or underutilized cropland.[14]

Another study likewise found that GHG projections from corn ethanol in the U.S. would be significantly reduced if market-mediated responses and by-product use were factored into the analysis.[15] A recalculation using these factors reduced cropland conversion of land used for the ethanol feedstock by 72%. Consequently, the estimated GHG release was roughly one-quarter of Searchinger and colleagues' estimate of releases attributable to changes in indirect land use. Nonetheless, it was enough to cancel out the benefits of corn ethanol for avoiding global warming. While these studies had different detailed results, none were close to zero, and all were large enough to make the indirect land use emissions a large contribution to the life cycle costs.

Biofuels thus can be produced in such a way that they have lower net GHG emissions than fossil fuels, but estimated emissions vary widely among studies. Some of these differences are associated with feedstock choice, plant growth and harvest methods, and production processes, while other differences reflect varying analytical methodologies. Using consistent methodologies to develop systematic comparisons would help clarify the consequences of different choices among biofuels sources and growth and production methods.

Water Use and Quality

Biofuels production can affect both water availability and water quality. The impacts of different biofuel crops on water depend on many factors, including fertilizer application, tillage, soil type, and whether the crop is replacing a different type of vegetation.

Water Use

The greatest water use in biofuels production is for growth of the crops. For biofuels crops such as corn and sugar cane, 99% of the water needed is for growth of the feedstock.[16] The amount of water used to produce biofuel corn varies greatly depending on climate, with the total water required for irrigation and processing in the U.S. ranging from 5 liters per liter ethanol in Ohio to 2,138 liters in California[17] and up to 2,570 liters globally (Table 2). Refining ethanol from the feedstock requires just 3–6 liters of water per liter of ethanol. Thus, although processing plants may have localized impacts on water supply, the water demand for growing biofuel crops is a bigger concern than for processing. These numbers, however, mask wide variation in irrigation practices. Although increased biofuels production is not expected to alter national water availability in the next 5 to 10 years, regional and local impacts can be expected in areas where water resources are already stressed. Consumptive water use for biofuel between 2005 and 2008 grew at almost twice the rate of growth in ethanol production, indicating that biofuel agriculture had expanded into areas where enhanced irrigation was required. In some Western states groundwater resources are being depleted rapidly for irrigation of biofuel corn.[17] There are even more water-intensive crops than corn being grown throughout the world for biofuels (Table 2), and in the next four decades irrigation for biofuel crops is expected to increase by 14 to 45%.[18]

The water requirements of biofuel crops should factor into any policy to implement a robust and environmentally sustainable national biofuels program. Biofuels production can be consistent with sustainable water use, given energy conservation, water use planning, and careful agricultural practices. One strategy is to limit expansion of dedicated bioenergy crops to areas where irrigation is not required and locate biorefineries in areas that do not depend on irrigated corn feedstock.[17,19] Even where irrigation is intermittent, groundwater irrigation can quickly reduce any GHG emissions benefits of biofuels because of the fossil energy needed to pump water from deep underground to the surface.

Water use efficiency varies from crop to crop. Switchgrass, like other perennial biofuel plants with deep roots, generally uses water more efficiently than do shallow-rooted annual crops. Switchgrass can be 1.8 to 5.0 times more efficient than corn, depending on the site and assuming that all the corn stover is not removed.[20] However, the total consumptive water use is higher for switchgrass and miscanthus, another perennial grass, because of the longer growing season for perennial biofuel crops.

Algae can be cultivated either in ponds or enclosed, transparent containers called photobioreactors. As illustrated by the values in Table 2, pond production requires far more water. Optimizing where algae are grown—concentrating production in sunny, humid climates where evaporation is minimized—could reduce water use by 75%.[21] Cultivation of marine algae either in coastal areas or using saline groundwater could also reduce freshwater use.

Water Quality

Water quality can be degraded by expansion of biofuels production from high intensity monoculture agricultural practices. In the U.S., industrial agriculture causes soil erosion and runoff of nitrogen, phosphorus, and pesticides into local waterways and groundwater. Among the consequences is long-distance transport of nutrients to estuaries such as the Gulf of Mexico where it leads to hypoxia and anoxia across thousands of square miles. Hypoxia (low oxygen) and anoxia (no oxygen) create dead zones where the oxygen level is too low to support animal life.

Reducing hypoxia in the Gulf will be increasingly difficult given the ambitious targets set for renewable fuel production. Agricultural sources, especially corn, are estimated to contribute more than 70% of the total nitrogen and phosphorus delivered to the Gulf of Mexico[22]. Meeting the grain-based biofuels target could increase the annual dissolved inorganic nitrogen carried into the Gulf of Mexico by the Mississippi and Atchafalaya Rivers by 10–34%.[23]

Because agrochemicals bind with soil particles, soil loss through erosion is also an important factor in water quality. According to EPA, corn produced on the same fields year after year results in higher infestation of corn pests, which can lead to greater pesticide use and pesticide leaching to waters. Similar concerns about soil erosion, sedimentation, and nitrogen use have been raised about sugarcane, another major source of ethanol, particularly in Brazil.[11] Additional studies of the

Table 2. Water use of various biofuel feedstocks

Feedstock type	Water use (volume used per volume fuel produced)
Ethanol feedstocks	
Corn (Maize)	5-2,570[a,b,c] (depending in part on irrigation)
Switchgrass	2.9 – 423 (depending in part on irrigation)[b]
Sugar beet	1,388[a]
Potato	2,399[a]
Sugar cane	2,516[a]
Cassava	2,926[a]
Barley	3,727[a]
Rye	3,990[a]
Paddy rice	4,476[a]
Wheat	4,946[a]
Sorghum	9,812[a]
Biodiesel feedstocks	
Soybean	14-321(depending in part on irrigation)[b]
Algae (pond production)	25-1,421[b,d,e]
Algae (enclosed production)	30-63[b]

Sources:

[a] Gerbens-Leenes, W., A. Y. Hoekstra, and T. H. Van der Meer. 2009. *Proceedings of the National Academy of Sciences* 106(25): 10219-10223.

[b] Harto, C., R. Meyers, and E. Williams. 2010. *Energy Policy* 38: 4933–4944.

[c] Chiu, Y.W., B. Walseth, and S. Suh. 2009. *Environmental Science and Technology* 43: 2688-2692.

[d] EPA. 2010. Renewable Fuel Standard Program (RFS2) regulatory impact analysis. EPA-420-R-10-006.

[e] Wigmosta, M. S., A. M. Coleman, R. J. Skaggs, M. H. Huesemann, and L. J. Lane. 2011. *Water Resources Research* 47: W00H04, doi:10.1029/2010WR009966.

interactive effects of feedstock choice, tillage practices, and crop rotation on erosion would help to address these concerns.

Use of bioenergy crops that require less fertilizer than traditional crops could improve regional water quality and reduce the annual decline in oxygen in the Gulf of Mexico. For example changing from corn to switchgrass and corn stover could decrease nitrate inputs to the Gulf by 20%[24], and model results suggest miscanthus could reduce nitrate leaching by 25% while increasing the amount of ethanol produced. Switchgrass and other perennial crops with long-lived roots also help to prevent sediment runoff.

Biodiesel, still a small percentage of the U.S. biofuels produced, offers promise for improving water quality because the primary source of biodiesel in the U.S. is soybeans. Soybeans, like other plants in the bean family, convert nitrogen efficiently into a usable form through nitrogen fixation and require little if any additional nitrogen fertilizer. Per unit of energy gained, biodiesel derived from soybeans requires just 2% of the nitrogen and 8% of the phosphorus needed to produce corn ethanol.[25] Pesticide use is also lower for soybeans than corn. High-diversity prairie grasslands that require only low inputs of phosphorus would also compare favorably relative to corn using this metric.[4]

While refining the feedstock into fuel creates polluted water, there is far less water involved, so the overall impact is less.

Figure 4. Effect of various factors on wildlife habitat and biodiversity. For each factor, the qualities associated with greater wildlife benefit (or less impact) are listed on the right side of the figure, and the qualities that are associated with less wildlife benefit (or greater impact) are listed on the left side of the figure.

Wildlife habitat value

Lower		Higher
Cropland	**Habitat type**	Diverse native habitats
Exotic monocultures	**Plant diversity**	Diverse native grasslands/forests
Non-native, invasive	**Invasiveness of planted materials**	Native, non-invasive
Breeding/nesting season	**Harvest and disturbance timing**	Late fall, early spring
Multiple harvests per year	**Harvest frequency**	One harvest per year, or less
Little or no stubble remaining	**Stubble height post-harvest**	Tall stubble or plant regrowth
No unharvested area in field or nearby	**Habitat refugia**	Unharvested area within field
Isolated patch/field	**Landscape context**	Complex of habitat patches/fields

Wildlife impact

Higher		Lower
Native prairie/forest/wetland	**Land use replaced with biomass crop**	Existing or marginal cropland
High input	**Fertilizer/pesticide use**	Minimal input
Annual crops – high erosion	**Soil erosion and sedimentation**	Perennial plants – low erosion

Adapted from Fargione, J. E., T. R. Cooper, D. J. Flaspohler, J. Hill, C. Lehman, T. McCoy, S. McLeod, E. J. Nelson, K. S. Oberhauser, and D. Tilman. 2009. *BioScience* 59:767–777.

According to EPA's regulations for the Renewable Fuel Standard program, 40 CFR 80, the largest water discharge from ethanol refineries is brine (saltwater), which is produced when process water is treated before use. For every two liters of pure water produced, about a liter of brine is discharged. These brines are not treatable, except by dilution or by further concentration and disposal. Refineries also discharge some cooling water to avoid buildup of minerals in the cooling system, and off-batch ethanol, which can increase biological oxygen demand in receiving streams. Other potential pollutants are regulated by the Clean Water Act.

The overall effects of biofuels production on water use and quality are primarily associated with the production of crops; refining the feedstock into ethanol or biodiesel has local water quality effects. Choices of crops and the methods for growing them (irrigated vs. non-irrigated terrestrial crops, algae grown in ponds vs. enclosed containers) in turn are the major determinants of water impacts of biofuels production.

Biodiversity

Biodiversity, broadly defined as the variety of organisms that inhabit ecosystems as well as the variety of ecosystems themselves (e.g., grasslands, forests, wetlands), may be affected by expansion of biofuels production. To understand the impact of biofuels production on biodiversity, we evaluate effects that accompany land conversion and use, changes in inputs of residue, nutrients, chemicals, and water, species selection for production and the potential invasiveness of these species, and the impact of different production processes.

Direct Impacts of Land Conversion

The primary factor determining impacts on biodiversity is the location of production. Biofuels crops can replace existing crops or native vegetation, or can be grown on agricultural lands that are not currently in production. The net effect of crops on wildlife will depend on the land use they replace.[26] Figure 4 depicts how different parameters of cropping systems, such as number of harvests, crop diversity, and chemical inputs, affect biodiversity. In tropical regions, expansion of biofuel crops such as sugarcane and oil palm into intact native vegetation threatens to destroy some of the world's most diverse ecosystems. Conversion of natural habitats also has significant consequences for GHG emissions, as described above.

Direct conversion of natural ecosystems for growing biofuels is less of an issue for the U.S. than it is for tropical areas of the world because expansion of biofuel crops in the U.S. will mostly occur in areas that are now or recently in agricultural production. The exception could be replacement of hardwood forests by plantations of woody biomass crops such as hybrid poplars (*Populus* species). Woody biomass poses different challenges than agricultural crops because forests also provide a wide variety of other services, such as wood for construction materials, recreation, and wildlife habitat. As with farmed crops, the potential impacts of wood harvesting for liquid fuel production will vary depending on the source of the material. Challenges for developing woody biomass as a sustainable biofuel source include resource availability, impacts of various harvesting technologies, integrated management systems for energy and other goods and services provided by forests, and development and deployment of biomass-to-energy facilities.[27]

Meeting existing and proposed mandates for bioenergy and biofuels from wood could double the current level of wood harvesting in the U.S.[28] There is a need for improved supply and demand estimates as well as the development of standards for sustainable wood harvest practices and clear guidelines on the role of public lands in biomass supply. Forest harvest for biofuels poses challenges for biodiversity and will require management practices that protect the

Table 3. Summary of potential environmental effects of biofuels

Variable	Factors to consider	Potential effects
Greenhouse gas emissions (direct effects)	• Tilling of soil vs. no-till • Use of crop residue • Nitrogen fertilizer use • Feedstock choice • Water source	• Tilling reduces soil carbon, increasing GHG emissions; no-till conserves soil carbon. • Leaving crop residue on field conserves soil carbon. • Nitrogen fertilizer releases CO_2 when it is produced and leads to N_2O production when used. • Perennial, cellulosic feedstocks can reduce GHG emissions and conserve soil carbon. • Irrigation, if pumped, uses fossil fuels, releasing GHGs.
Greenhouse gas emissions (indirect effects)	• Land use change	• Conversion of forest or unfarmed perennial vegetation to biofuel crops can release large amounts of carbon from soil and existing vegetation. • More carbon must be captured by the crop than would have been captured had the land not been converted.
Water use	• Feedstock choice • Irrigation requirements	• Most water used for biofuels production is used during crop growth. • Fuel used to irrigate crops can produce GHGs. • Crops vary greatly in their water requirements (see Table 2). • Evaporative losses from open algal ponds can be large.
Water quality	• Feedstock choice • Fertilizer use	• Annual crops especially when tilled can increase soil erosion, sedimentation, pesticide leaching. • Nitrogen and phosphorus fertilizer use can increase nutrient loadings to groundwater and downstream water bodies. • Substituting perennial crops that require little fertilizer for annual crops can improve regional water quality.
Biodiversity	• Location of production • Feedstock choice • Feedstock management	• Conversion of native habitats or marginal agricultural lands to annual crop production can substantially reduce biodiversity. • Converting degraded lands to diverse perennial crops can improve biodiversity. • Annual crops like corn have a lower diversity of beneficial insects, birds, and other taxa than mixed perennial crops. • Some biofuel crops may become invasive. • Substituting diverse perennial crops for annual crops can significantly improve biodiversity. • Perennial feedstocks can be managed to protect biodiversity by carefully timing harvests and providing wintertime cover.

Box 5. Future Research Needs

Sustainable production of biofuels will require an integrated assessment of ecological dimensions and development of a transparent framework for evaluating tradeoffs among environmental, social, economic, and energy impacts. Such tradeoffs can be minimized or avoided by considering crop selection, indirect effects of land use, effects on soil biogeochemistry and biodiversity, social and economic factors, technological advancements, and more comprehensive life cycle assessments.

Crop Selection

We need a better understanding of which cropping systems by region will provide the greatest energy return with the least impact and the smallest energy inputs. Specifically, in what ways can feedstocks be grown with conservation tillage practices? What feedstocks provide a greater net energy output? What are the land requirements to support energy-efficient feedstocks?

In addition, it is likely that crop systems will be developed for additional species and growing conditions; this may entail genetic modification or the introduction of nonnative species. Moreover, many of the plant characteristics being selected for dedicated biofuel feedstocks will increase the probability of these species escaping cultivation and becoming invasive species. Future research is needed to develop screening protocols for assessing the potential for biofuel species to become invasive.

Land Use

Research is needed on how best to design agricultural landscapes to deliver optimum environmental benefits while enhancing farm income through a mix of commodity and conservation revenue streams. This research should investigate how conversion to biofuel crops will affect the conservation benefits of reserve programs and how changes in crop rotations will affect long-term soil productivity. The cost/benefit of moving marginal lands (including acreage that has been taken out of production of annual crops for conservation purposes) into production of perennial feedstocks needs to be scientifically assessed.

Effects on Soil Biogeochemistry and Biodiversity

The overall impacts of biofuels production on the nitrogen cycle are not well understood, including the extent to which different energy crops and production practices increase or decrease N_2O emissions and nitrate runoff. Also poorly understood is how removal of crop residue (e.g., corn stover) affects soil chemistry and soil structure—and thus carbon sequestration, soil fertility, and soil erosion—and how removal of woody biomass affects forest health. Beyond some threshold, removal of forest and agricultural residues may risk damage to soil health and productivity, nutrient cycling, stand structure, and water quality. However, the level of these thresholds and the factors that cause them to vary from field to field or woodlot to woodlot are not well understood. In addition, we don't yet understand what effect removing biomass from forest ecosystems will have on any wildlife or plant group (especially terrestrial insects, fungi and mycorrhyzal associations, smaller animals low on the forest food chain, and rare plant communities).

Social Factors

The development of cooperatives producing ethanol has been very beneficial to many rural Midwest economies. Local ownership has economic, social, and environmental advantages that are not fully understood and need to be quantified. In addition, local and farmer ownership is rapidly being replaced with corporate and absentee ownership, which can result in unsustainable practices. Research is needed to address how these ownership changes affect the environmental and economic sustainability of rural communities.

Production of biofuels from sustainable perennial feedstocks not only can benefit local communities but also can reduce the environmental effects on "downstream" communities and rural communities in other countries. Research is needed to provide a better understanding of how incentives for crop-based biofuels production influence not only local and regional land-use decisions in the United States but also land-use decisions in other countries, some of which may result in deforestation or a loss of crops being grown for food or fiber.

Biofuels production systems should focus on linking energy, food and fiber production, and natural resource objectives. System design should support the cultural transition needed to shift from corn ethanol to perennial and cellulosic systems, which are likely to have lower adverse environmental impacts and greater benefits.

Economic Factors

Several economic questions dominate discussions of biofuels development. How much land is necessary to produce cellulosic biofuels at a national level, and how much of the overall energy needs of the nation can be satisfied by this production? To what extent are economic incentives necessary? There is a high level of uncertainty in predicting how biofuels production will affect food prices, international grain markets, production of other crops, and aid to other countries. Similarly, expansion of biofuels production could significantly affect other energy sources, industries depending on abundant water supplies, and recreation-related uses of land or water.

A fundamental challenge is how to balance economies of scale of production (field and industrial) with local and national environmental and economic needs. The optimum scale of biofuels production systems needs to be determined, taking into account the local environmental, ecological, and economic impacts. Specifically, how does scaling affect communities and what are the benefits of small-scale, decentralized energy production? How does scaling up technologies affect externalities that are not built into the cost of production, such as deforestation and other land use conversions?

Technology Development

Foremost, technological increases in the economic efficiency of biofuels production systems should result in lower overall environmental impact of these systems. For example, technological advances in fermentation could lead to products with greater energy content that don't need to be distilled and that could be transported through extant petroleum-distillate pipelines rather than by vehicles. Therefore, research is needed to improve the efficiency of conversion to fuels and reduce production costs. Research should also focus on developing perennial biofuel crops that provide value-added co-products (extractable enzymes, nutrients, food proteins, etc.). Because source-specific equipment for planting, cultivating, harvesting, and processing could present a major economic hurdle to flexibility, engineering processes will need to be designed to accommodate the interchangeability of crops. Moreover, research is needed to assess the use of waste materials, higher-efficiency feedstocks, and future-generation biofuel sources, such as algae, as potential substitutes for food resource feedstocks.

Integrated Life Cycle Assessments

Determining the conditions under which biofuels production systems are a net energy benefit and are environmentally and socially sustainable will require transparent, flexible, and spatially explicit life cycle assessments at local, regional, and global scales. Specifically, life cycle assessments are needed that calculate the net energy production, greenhouse gas footprints, and environmental degradation of renewable energy systems. Greater attention should focus on investigating, measuring, and accounting for the indirect implications of biofuels production systems.

environment and complexity of forests while accommodating the expansion of markets for woody biomass.[29] One field study found fewer species of all groups of vertebrates inhabiting biofuel plantations (poplar, pine, and row crop) than in reference sites (natural forests and pastures), and lower abundance of both birds and mammals.[30]

Although algal biofuels production is still in experimental and pilot stages, one of its appeals is lower land use impact than conventional biofuels. Because algae grow rapidly in confined tanks or ponds, they use land more efficiently than corn, switchgrass, or rapeseed. Meeting today's energy needs in the U.S. by biofuels would require 41% of the land area for corn, 56% for switchgrass, or 66% for rapeseed, but only 3-13% for algae, especially if algal production were concentrated in regions where water-use efficiency is optimized.[5, 21, 31] Moreover, because algae can be grown on non-productive land, there may be less competition for arable land currently used for growing food crops.

Retired agricultural land or "marginal" agricultural lands that are subject to strict cropping limitations may be the habitat types where growing biofuel crops could have more serious implications for biodiversity. The U.S. Department of Agriculture established the Conservation Reserve Program (CRP) in 1985 "to help control soil erosion, stabilize land prices and control excessive agricultural production." Under the CRP, land is removed from production so that natural resources—soil, water, vegetative cover—can be improved. By creating wildlife habitat where row crops would otherwise be planted, the CRP enhances biodiversity and is particularly important for certain groups of species. The USDA describes the CRP as "a major contributor to increased wildlife populations in many parts of the country," and the program has been credited with helping maintain populations of grassland birds and migratory ducks while improving the quality of freshwater stream ecosystems.[19, 26, 32] Biofuels crop expansion may create incentives for land to be removed from the CRP. Demand for biofuels could affect landowner decisions about CRP enrollment and Congressional efforts to increase agricultural production. However, these decisions are affected by many other factors as well.

Biofuel demand is also engendering greater scrutiny of marginal lands, which can be broadly described as lands not currently in commercial use. A modeling study of different conversion scenarios for marginal lands in the Midwest concluded that expansion of annual biofuel crops such as corn and soybeans would cause bird species richness (abundance and diversity) to decline by 7-65% across a sizable portion of the landscape.[33] Conversely, if annual crops were replaced with perennial crops, bird species richness could increase 12-207%.

Some of the species grown for biofuels may become invasive. Unfortunately, traits that make some crop species appealing as biofuel alternatives—drought tolerance, rapid growth, pest resistance—also make them good candidates for becoming invasive. Several species being developed as biofuel feedstocks, including miscanthus, are already invasive in certain regions.[34] Sterile strains produced through genetic modification appear promising for preventing escape, but biologists warn that some plants that do not produce fertile seed are still capable of becoming highly invasive.[35] Moreover, being native doesn't mean that a species is worry-free; plants native in one region can become devastating pests in another. Careful screening of any biofuel crops proposed for a specific area could help address these concerns.

Risks associated with invasive species in algal biofuels production have not been studied in detail. Releases of exotic or invasive algal species could alter the community composition of affected aquatic ecosystems. However, such concerns could be addressed through careful selection of species to be grown in specific locations. For example, in areas where releases to freshwater might be a concern, growing species that require saline water could reduce the risk of invasion. Releases are more likely from open pond systems, particularly during growth and harvesting, than from closed culture systems.

For reasons of expense and efficiency, feedstocks grown for biofuels in the U.S. are grown predominantly in monocultures, which by definition are biologically homogeneous rather than diverse. However, increasing crop diversity has been shown to yield significant environmental benefits. Research in agricultural settings has found that where crop diversity and structural complexity is high, so is diversity of other organisms such as birds and insects. Many of these are beneficial species, such as insects that consume aphids, that in turn help reduce pests.

There may be trade-offs between managing biofuels production for increased biodiversity and production, although the science is not yet clear. Several studies showed that mixed native grassland on infertile degraded lands had significantly higher energy yields than monocultures of corn, soybeans, or switchgrass. Other studies, however, have found that conservation grasslands with more plant species had significantly lower biomass yields and a lower ethanol yield per unit biomass than sites with fewer species.

Conclusions: Biofuels and Sustainability

A core argument for the development of biofuels is that they can contribute to social, economic, and environmental sustainability. Appropriately managed, biofuels can reduce GHG emissions, provide new sources of income to rural communities, enhance ecosystem services, and generally improve quality of life. However, as the discussions above reveal, there are tradeoffs that must be understood and acknowledged in order to optimize the socioeconomic and ecological benefits of biofuels, and an integrated research program is needed to help realize those benefits (Box 5 and Table 3).The Ecological Society of America[36] has enunciated three principles for sustainability in biofuels production:

1. *Systems thinking:* using a systems approach to assess the energy yield, carbon

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neutrality, water use, and the full impact of biofuels production on downstream and downwind ecosystems. More energy should be produced by the fuel than is consumed by its extraction and transport. Any fossil fuel carbon used in the production of biofuels should be offset by carbon sequestration elsewhere in the global system. And analyses must consider the effects on interconnected ecosystem processes such as nitrogen emissions from land to air, nitrate and phosphorus export to aquatic ecosystems, soil erosion, and other important impacts of agriculture on surrounding landscapes, including pests, nonnative species, and effects on wildlife or protected species.

2. Conservation of ecosystem services: biofuels production should be focused on managing landscapes for a wide range of ecosystem services, for example, nutrient cycling, sequestration of soil carbon, reduction of soil erosion and nitrous oxide production, and protection of pollinator habitats.

3. Scale alignment: sustainability must be assessed at landscape, regional, and global scales, because what is sustainable at one scale may be unsustainable at another. Criteria for sustainability have been developed by numerous organizations and scientists. The European Union's biofuels and bioenergy policy stipulates that GHG emissions must be reduced by least 35% and that biofuels must not be obtained from lands with high biodiversity value or high carbon stocks. These criteria are echoed in the principles for sustainable biomass production developed by the Nordic Council of Ministers, which include low GHG emissions, maintenance and enhancement of biodiversity, ecological processes and ecosystem functions, and protection of areas of high conservation value. Others suggest that biofuels should receive policy support as substitutes for fossil energy only when they make a positive impact on energy security, GHG emissions, biodiversity, and the sustainability of the food supply.

These criteria, which generally converge on maintaining ecosystem services, reducing GHG emissions, avoiding other adverse effects, and conserving biodiversity, emphasize the importance of a landscape approach. Several writers have articulated such an approach as a redesign of the agricultural landscape. Such a landscape would move away from simple ethanol production plants processing one kind of feedstock, for example, corn, toward integrated biorefineries capable of processing diverse feedstocks and producing not just fuel, but also a wide variety of biobased materials. This design could create the conditions for a sustainable, resilient biofuels production system based in a biologically diverse landscape that supports social, economic, and energy needs for the long term.

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