RESEARCH REPORT

Impacts of Biofuels on Climate Change, Water Use, and Land Use

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INTRODUCTION

Governments worldwide are promoting the development of biofuels, such as ethanol from corn, biodiesel from soybeans, and ethanol from wood or grass, in order to reduce dependency on oil imported from politically unstable regions of the world, spur agricultural development, and reduce the climate impact of fossil fuel combustion. Biofuels have been promoted as a way to mitigate the climate-change impacts of energy use because the carbon in a biofuel comes from the atmosphere, which means that the combustion of a biofuel returns to the atmosphere the amount of carbon dioxide (CO_2) that was removed by the growth of the biomass feedstock. Because CO_2 from the combustion of fossil fuels, such as oil, is one of the largest sources of anthropogenic climate-active "greenhouse gases" (GHGs), it might seem, at first blush, that the elimination of net CO_2 emissions from fuel combustion per se, as happens with biofuels, would help mitigate the potential for global climate change. It turns out, however, that this elimination of net CO_2 emissions is a small part of a complete accounting of the climate impacts of biofuels. Indeed, as I delineate here, calculating the climate impact of biofuels is so complex, and our understanding is so incomplete, that we can make only general qualitative statements about the overall impact of biofuels on climate. Moreover, the production of biofuels can have significant impacts on water use, water quality, and land use – because per unit of energy produced, biofuels require orders of magnitude more land and water than do petroleum transportation fuels – and these impacts should be weighed in an overall assessment of the costs and benefits of policies that promote biofuels.

At the start of each major section, I first discuss the overall metric by which impacts typically are measured. This overall metric is important because many analysts use it is a basis for evaluating and comparing the impacts of biofuels; hence, the overall metric should be as broad as possible yet still represent what society cares about. I argue that the absence of broad, meaningful metrics for climate-change, water-use, and land-use impacts makes overall evaluations difficult. Nonetheless, in spite of the complexities of the environmental and technological systems that affect climate change, land use, and water use, and the difficulties of constructing useful metrics, we are able to make some qualitative overall assessments. It is likely that biofuels produced from crops using conventional agricultural practices will *not* mitigate the impacts of climate change and will exacerbate stresses on water supplies, water quality, and land use, compared with petroleum fuels. Policies should promote the development of sustainable biofuel programs that have very low inputs of fossil fuels and chemicals, that rely on rainfall or abundant groundwater, and that use land with little or no economic or ecological value in alternative uses.

CLIMATE-CHANGE IMPACTS OF BIOFUELS

Over the past twenty years, researchers have performed hundreds of analyses of "CO_2-equivalent" (CO2e) GHG emissions from the lifecycle of biofuels. These analyses typically have estimated emissions of CO_2, methane (CH_4), and nitrous oxide (N_2O) emitted from the production of biofuel feedstocks (e.g., growing corn), the production of the biofuel (e.g., producing ethanol from corn), and the distribution and end-use of the biofuels (e.g., the use of ethanol in motor vehicles). Analysts multiply emissions of CH_4 and N_2O by their respective "Global Warming Potentials" (GWPs) and add the result to estimated emissions of CO_2 to produce a measure of total lifecycle CO2e GHG emissions. Several reviews discuss LCA of biofuels, results from biofuel LCAs, and issues in biofuel LCA (United Nations Environment Programme [UNEP], 2009; Menichetti and Otto, 2009; Reijnders and Huijbregts, 2009; Delucchi, 2006; Farrell et al., 2006; International Energy Agency, 2004). Here, I discuss problems with the CO2e metric, well-known and emerging issues in conventional LCAs, and other potentially important issues.

Problems with the CO2e metric.
As mentioned above, virtually all biofuel LCAs measure the climate impact of biofuels on the basis of the GWP of CO_2, CH_4, and N_2O emissions. The GWP estimates the radiative forcing of gas *i* (e.g., CH_4) relative to that of CO_2 integrated (typically) over a 100-year period, accounting for the decay of the gas in the atmosphere and the direct and indirect radiative forcing (IPCC, 2007). Hence, biofuel LCAs estimate the total relative radiative forcing over a 100-year period, for three GHGs.

There are several problems with this metric (IPCC, 2007; Fuglestvedt et al., 2003; Bradford, 2001). First, we care about the impacts of climate change, not about radiative forcing per se, and changes in radiative forcing are not simply linearly correlated with changes in climate impacts. Second, the method for calculating the GWPs involves several unrealistic simplifying assumptions, which can be avoided relatively easily. Third, by integrating radiative forcing from the present day to 100 years hence, the GWPs in effect give a weight of one to every year between now and 100 and a weight of zero to every year beyond 100, which does not reflect how society makes tradeoffs over time (a more realistic treatment would use continuous discounting). Fourth, the conventional method omits several gases and aerosols that are emitted in significant quantities from biofuel lifecycles and can have a significant impact on climate, such as ozone precursors, carbon monoxide (CO), nitrogen oxides (NO_X), sulfur oxides (SO_X), and black carbon (BC).

Some preliminary work indicates that a method for estimating CO2e factors that addresses the shortcomings above can produce comparative assessments that are appreciably different from those that use traditional GWPs and consider only CO_2, CH_4, and N_2O (Delucchi, 2003, 2006).

Well-known and emerging issues in conventional biofuel LCA. In most biofuel LCAs, the estimated CO2e climate impact (based on GWPs, as discussed above) is a function of four factors, the first three of which have long been known, and the fourth of which is an important emerging issue (UNEP, 2009; Börjesson, 2009; Menichetti and Otto, 2009; Reijnders and Huijbregts, 2009): 1) the amount and kind of fossil fuel used in cultivation of biomass feedstocks and in the production of the biofuel; 2) the amount of nitrogen fertilizer applied, and the assumptions regarding N_2O emissions from that fertilizer; 3) the benefits of any co-products of the biofuel production process (e.g., animal feed is produced along with ethanol in corn-to-ethanol plants); and 4) the assumptions and analytical methods concerning carbon emissions from land-use change (LUC). As Börjesson (2009) notes, "depending on these four factors, production systems for ethanol may mean anything from major climate benefits to increased emissions of GHG compared with petrol" (p. 593).

Börjesson's (2009) conclusion, however, applies mainly to biofuels derived from agricultural crops such as corn, soybeans, and wheat – so-called "first-generation" biofuels. It certainly does not apply to biofuels derived from waste products (which however are usually available only in small quantities), and it applies with less force to so-called "second-generation" biofuels derived from cellulosic sources such as grasses and trees. Compared with biofuels from agricultural crops, cellulosic biofuels generally require less fertilizer (and hence produce less N_2O), use non-fossil sources of energy (such as part of the plant material) in the production of the biofuel (and hence do not emit fossil-CO_2), and in some circumstances cause lower emissions related to LUC on account of the relatively high carbon stocks maintained in the soils and biomass of grass and wood plantations. In the best case, if cellulosic biofuels are derived from mixed grasses grown on degraded lands with little management and low inputs (Tilman et al., 2006), lifecycle CO2e emissions almost certainly will be lower than from petroleum fuels.[2]

Potentially important issues that have not been investigated in the context of biofuel LCA.

The production of biofuels will cause at least two kinds of changes in the environment that are likely to have major impacts on climate but that have not yet been included in any published biofuel LCAs: changes in biogeophysical parameters due to changes in land use, and perturbations to the nitrogen cycle due to the use of nitrogen fertilizer.

Biogeophysical impacts. Changes in land use and vegetation can change physical parameters, such as albedo (reflectivity) and evapotranspiration rates, that directly affect the absorption and disposition of energy at the surface of the earth and thereby affect local and regional temperatures (Bala et al., 2007; Marland et al., 2003). Changes in temperature and evapotranspiration can affect the hydrologic cycle, which in turn can affect ecosystems and climate in several ways, for example via the direct radiative forcing of water vapor, via evapotranspirative cooling, via cloud formation, or via rainfall, affecting the growth and hence carbon sequestration by plants.

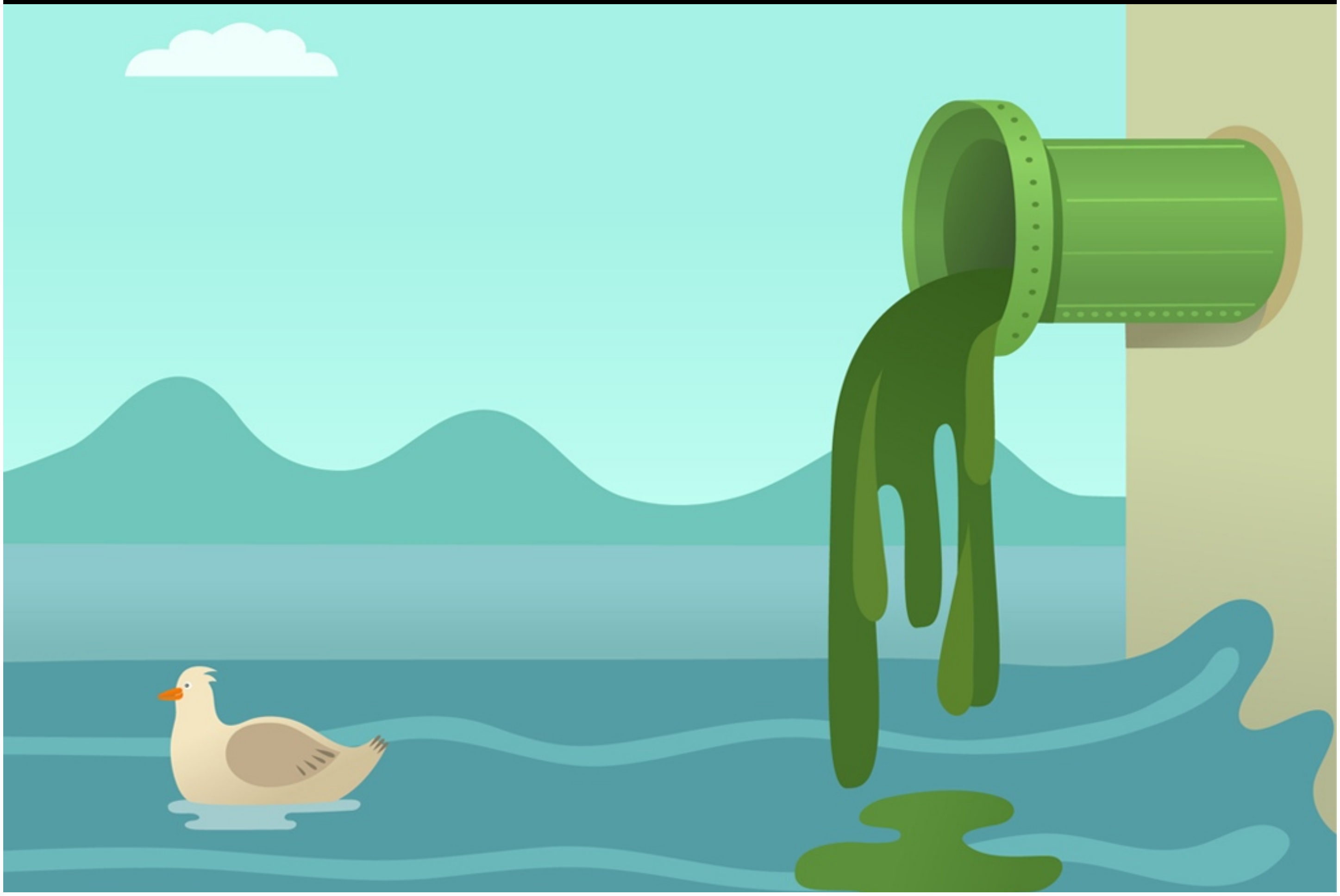
In some cases, the climate impacts of changes in albedo and evapotranspiration due to LUC appear to be of the same order of magnitude but of the opposite sign as the climate impacts that result from the associated changes in carbon stocks in soil and biomass due to LUC. This suggests that the incorporation of these biogeophysical impacts into biofuel LCAs could significantly change the estimated CO2e impact of biofuel policies.

The nitrogen cycle. Anthropogenic inputs of nitrogen to the environment, such as from the use of fertilizer or the combustion of fuels, can disturb aspects of the global nitrogen cycle and ultimately have a wide range of environmental impacts, including eutrophication of lakes and coastal regions, fertilization of terrestrial ecosystems, acidification of soils and water bodies, changes in biodiversity, respiratory disease in humans, ozone damages to crops, and changes to global climate (Galloway et al., 2003; Mosier et al, 2002). Galloway et al. (2003) depict this as a "nitrogen cascade," in which "the same atom of Nr [reactive N, such as in NO_X or NH_Y] can cause multiple effects in the atmosphere, in terrestrial ecosystems, in freshwater and marine systems, and on human health" (p. 341; brackets added).

Moreover, nitrogen emissions to the atmosphere, as NO_X, NH_Y, or N_2O, can contribute to climate change through complex physical and chemical pathways that affect the concentration of ozone, methane, nitrous oxide, carbon dioxide, and aerosols. Yet even though the development of many kinds of biofuels will lead to large emissions of NO_X, N_2O, and NH_Y, virtually all lifecycle analyses of CO2e GHG emissions from biofuels ignore all N emissions and the associated climate effects except for the effect of N fertilizer on N_2O emissions. Even in the broader literature on climate change there has been relatively little analysis of the climate impacts of N emissions, because as Fuglestvedt et al. (2003) note, "GWPs for nitrogen oxides (NO_X) are amongst the most challenging and controversial" (p. 324).

Summary of climate-change impacts.

Nobody has yet done an analysis of the climate-change impacts of biofuels that uses a metric for the impacts of climate change that considers all of known or suspected potentially important climate-altering effects. As a result, we cannot yet make quantitative estimates of the climate impacts with confidence. However, we can make some useful qualitative statements. It is likely, for example, that biofuels produced from crops using current agricultural practices will *not* offer appreciable reductions in CO2e climate impacts, and might even exacerbate climate change, compared with the impact of petroleum fuels. At the other end of the spectrum, we know that biofuels produced from true waste material (i.e., material with no alternative use) do not, by definition, affect agricultural practices or land uses, and hence will not significantly exacerbate climate change, unless the fuel-production process uses significant amounts of fossil fuels or fuel combustion produces nontrivial amounts of non-CO_2 GHGs. Similarly, biofuels produced from cellulosic materials, such as grasses, that are grown in the most ecologically sustainable manner possible, are likely to cause less climate-change damage than do petroleum fuels.



With our current knowledge, however, it is difficult to asses the impact either of biofuels produced from crops using the *best*, most sustainable practices, or of biofuels produced from cellulosic materials using practices similar to those in conventional agriculture. In order to assess these production systems, and in general to provide more comprehensive assessments of the climate impacts of biofuels, we need improved, integrated lifecycle/economic/environmental-systems models, able to address the problems discussed here.

WATER USE AND WATER QUALITY

The production of biofuels can require orders of magnitude more water than does the production of petroleum fuels (Mishra and Yeh, 2011; Gerbens-Leenes et al., 2009; King and Webber, 2008). This high demand for water can stress water supplies and degrade water quality via salinization and pollution from agriculture and industry (Zimmerman et al., 2008; Shah et al., 2000). Unfortunately, there is no commonly used single metric that captures all relevant aspects of the impacts on water availability and water quality. Instead, most studies provide a relatively simple measure of water consumption or water use, or a measure of one specific impact on water quality, eutrophication. I discuss both of these measures (water use and eutrophication) here. In a separate section, I provide simple, original estimates of the water use of biofuel systems relative to some pertinent measures of water availability.

Impacts on water consumption and water use.
Milà i Canals et al. (2009) distinguish two kinds of water inputs to production systems, "blue" water (in groundwater) and "green" water (from rainfall), and two kinds of water outputs from production systems, non-evaporative uses (corresponding to water withdrawals or water use in other classifications) and evaporative uses (corresponding to water consumption in other classifications). Generally, water withdrawal is water removed from the ground or diverted from a surface-water source, and water consumption is equal to total withdrawals less the amount that is not available for re-use.

Measures of water usage, expressed in terms of volume of water per unit of biofuel energy output, are more meaningful when they are expressed relative to some measures of water availability. But even when expressed relative to water availability, measures of direct water use do not fully represent the impacts society cares about, because the measures still do not capture the costs of water supply, the costs of water treatment, adaptive responses, the possibility of water trade, the impacts of water pollution, and so on. However, it is possible at least to incorporate into a water-use metric a simplified treatment of one of the most important of these impacts, water pollution.

Measuring impacts of water pollution. The production and use of biofuels can cause water pollution from fertilizer and pesticide runoff from crop fields and effluents from biofuel production facilities (Simpson et al., 2009). It is convenient to express the impacts of this pollution in terms of water use, because this then can be added to actual water usage to provide a broader index. The common way to do this is to estimate the amount of clean water that would be required to dilute polluted water to acceptable levels. Generally, pesticides require greater dilution than does phosphorus, which in turn requires greater dilution than does nitrogen. In round numbers, the amount of water required to dilute phosphorous pollution is of the same order of magnitude as the total direct water consumption (rainfall plus irrigation), for all crops, and is many times higher than the amount of water used for irrigation where irrigation is a small fraction of the total.

Eutrophication. A number of studies measure a specific impact of biofuel production on water quality, eutrophication. Increased concentrations of certain nutrients, particularly nitrogen and phosphorous, can promote excessive plant growth and decay in aquatic ecosystems, leading to increases in phytoplankton, decreases in dissolved oxygen, increased turbidity, loss of biodiversity, reductions in commercially important fish, increases in toxic plankton species, and other undesirable ecological effects (Simpson et al., 2009).

To the extent that the production of biofuel feedstocks uses large amounts of nitrogen and phosphorous fertilizer, the runoff from production fields into water bodies can cause significant eutrophication. To represent this, researchers typically estimate a phosphate-equivalent (sometimes nitrate-equivalent) "eutrophication potential" (analogous to the CO_2-equivalent global warming potential discussed above), calculated by multiplying nitrogen and phosphorous emissions by a "fate factor," which represents the fraction of the emitted pollutant that reaches the aquatic environment (this is 1.0 in the case of direct emission to water), and by an "effect factor," which represents the potential production of phytoplankton per gram of the pollutant relative to the potential production from a gram of phosphate (Brentrup et al., 2004).

Several studies have applied eutrophication potentials to lifecycle analyses of biofuels (e.g., UNEP, 2009; Baral and Bashki, 2008). Although these studies use a relatively simple metric for eutrophication impact, as discussed above, they all indicate the production and use of biofuels can cause greater eutrophication than does the production and use of petroleum fuels.

LAND USE

Per unit of energy produced, biofuels require orders of magnitude more land than do petroleum fuels (MacDonald et al., 2009; California Air Resources Board, 2009).
The land requirement per unit of delivered biofuel can be calculated simply as the product of the yield (crop output per unit area), the production intensity (energy per unit crop), and a factor that accounts for the land-use impacts of any co-products of the production process. McDonald et al. (2009) use this method to estimate the land-use intensity of different energy production techniques, and find that biofuels require roughly 10 to 20 times more land per unit of area than do fossil fuels in the year 2030.

However, the land requirement for biofuel production is just a rough indicator of other land-use impacts that society cares about, such as soil erosion, dust and smoke from agricultural activities, loss of habitat, biodiversity, and ecosystem services, and the effects of competition for land on the prices of commodities and services produced by land.

Loss of habitat, biodiversity, and ecosystem services. The use of monocultural feedstocks (such as corn) to make biofuels can reduce biological diversity and the associated bio-control services in agricultural landscapes (UNEP, 2009; Reijnders and Huijbregts, 2009). A simple land-use intensity metric is not a good indicator of these impacts, in part because it does not reflect the impact of the land use on habitat integrity, wildlife corridors, and interactions at the "edges" of the affected area. To address this, researchers have proposed a number of more direct indicators, including the "Natural Degradation Potential" (Brentrup et al., 2002) and the "Ecosystem Damage Potential" (Koellner and Scholz, 2007). By any of these measures, biofuels made from crops can severely degrade natural habitats.

Soil erosion. Biofuel-crop harvesting practices can affect soil erosion and the nutrient and organic content of the soil, which in turn can affect the use of fertilizer (Reijnders and Huijbregts, 2009). For example, if crop residues are removed from the field and used as a source of energy in the production of a biofuel, then soil erosion might increase and fewer nutrients and less organic matter might be returned to the soil (Pimentel and Lal, 2007). Additional fertilizer may be required to balance any loss, and the use of additional fertilizer will result in additional environmental impacts.

Effects of competition for land on prices of commodities and services produced by land. As Rajagopal and Zilberman (2008) note, "allocating land for biofuels means taking land away from other uses like food or environmental preservation" (p. 70). Economic theory and economic models tell us that a demand-driven increase in the price of a biofuel feedstock, such as corn (for corn-ethanol), will benefit the producers of the feedstock but cost those who consume the feedstock directly or use it as a factor of production (Elobeid et al., 2006). In many if not most cases, the people who benefit tend to be wealthy, and the people who lose tend to be poor (Vanwey, 2009).

It is clear, then, that a main effect of the competition for land between biofuel crops and food crops will be higher food prices, which will hit the poor particularly hard. Indeed, if the

competition between biofuel crop production and food crop production is extensive and severe enough, it is possible that the consequent increases in agricultural prices will cause some people to go hungry and even starve (Runge and Senauer, 2007).

EXAMPLE CALCULATIONS OF THE LAND AND WATER REQUIREMENTS

In order to put the discussion of water and land impacts into a realistic context, elsewhere (Delucchi, 2010) I have estimated the impacts of developing the biofuels program that is part of a comprehensive set of global energy projections by the International Energy Agency (IEA, 2008). The IEA scenarios include detailed assumptions about technology and energy uses for power, transportation, and end use. The IEA's "Blue MAP" scenarios, in which biofuels provide 27 percent of total ground transportation energy in the world, requires:

- 6% of current global permanent pasture land;
- 16% of current global arable land;
- 6% of global renewable freshwater;
- 117% of current global water use by agriculture; and
- 82% of current total global water use.

For every 10 percent of the IEA-projected *global* ground transportation energy demand satisfied by cellulosic biofuels, the land and water requirements are:

- 2% of current global permanent pasture land;
- 6% of current global arable land;
- 2% of global renewable freshwater;
- 44% of current global water use by agriculture; and
- 31% of current total global water use.

Note that these calculations assume the use of "second-generation" cellulosic biofuels. The water use of "first generation" biofuels, ethanol from irrigated corn or biodiesel from irrigated soy, is somewhat higher than the water use of cellulosic biofuels (Delucchi, 2010).

Note also that all of these percentages are with respect to the current situation, and hence do not reflect increases in demand for land and water in other sectors, particularly agriculture. Several studies project that total global water withdrawals could increase by more than 20 percent by 2025, leading to severe water stresses in several regions of the world (e.g., Seckler et al., 1999). In the longer term, the number of people living in regions experiencing high stresses on water supplies (defined as less than 1,000 m^3/capita/year) could increase by several billion, with most of the increases occurring China, India, West Asia, and North Africa (Arnell, 2004). However, even if future freshwater withdrawals for all uses other than biofuel feedstock production were to double by 2050, the addition of the water demand estimated for the IEA "BLUE Map 2050" scenario analyzed above still would result in a total water withdrawal of just under 20% of the total global renewable freshwater resource – below the level considered to seriously "stress" water supplies.

Thus, even though the land and water requirements of biofuels are very large with respect to the requirements of current transportation energy systems, on the one hand, and large with respect to the requirements of current agricultural systems, on the other, at the *global* level there will be no evident water and pasture-land resource constraints on the development of bioenergy for several decades, unless the requirements of other sectors have been vastly underestimated.

Still, water and arable land are not distributed uniformly across the globe with respect to population or energy demand, and as a result at the regional level there can be severe constraints on land and water availability. In parts of China, South Asia, West Asia, and Africa current demands already are stressing water supplies, and these stresses are expected to increase dramatically in the coming decades (Alcamo et al., 2003; Seckler et al, 1999). The development of biofuel feedstocks in these areas could place intolerable stresses on water supplies (Müller et al., 2008; Fraiture et al., 2008). Even in the United States, a major expansion of biofuel production could seriously exacerbate water-quantity and water-quality problems (National Research Council, 2008). To avoid these regional water-availability constraints on biofuel production, biofuels would have to be traded globally, the way petroleum fuels are today. If in fact biofuel feedstocks can be grown in water-rich regions at reasonable cost and with minimal environmental impact, and if future demands for land and water by other sectors do not dramatically exceed present expectations, then arguably biofuel production need not be constrained by the global availability of land and freshwater.

Producing biomass energy feedstocks with lower impacts on climate change, water use, water quality, and land use. The environmental impacts of producing bioenergy feedstocks can be reduced by mixing plant species, reducing energy and chemical inputs, managing material flows to achieve nearly a closed system, and targeting biofuel crop production to degraded or abandoned lands (Tilman et al., 2006; Reijnders, 2006; Muller, 2009). For example, Tilman et al. (2006) propose that low-input, high-diversity (LIHD) mixtures of native grassland perenials in the U. S. can provide more biodiverse habitat and even higher yields than can monocultural perennials, at least on relatively infertile soils. They suggest that LIHD systems can be grown successfully on abandoned, degraded agricultural lands, and actually improve the quality of soil and water on such lands. (However, this improvement is relative to leaving the land degraded, not relative to restoring the land to its most environmentally beneficial use.)

However, it is not clear that such bioenergy systems can be sustainable and commercially viable at large scales. For example, Johansson and Azar (2008) suggest that it is unlikely that commercial bio-energy farmers will *choose* to grow bioenergy crops on degraded land, as it is likely to be relatively unprofitable. Similarly, Sala et al. (2009) note that while some small-scale biofuel production systems can maintain high biodiversity, “it is unlikely that solutions that produce biofuels while maintaining bio-diversity can be implemented at the scale necessary to meet current biofuel demand” (p. 131).

CONCLUSIONS

Research over the past two decades has helped us understand many aspects of the impacts of biofuel development on climate change, water use, and land use. However, because of the complexity of the ecological, economic, and technological systems that affect climate change, land use, and water use, and the difficulty of constructing useful metrics of impacts, there are as yet no definitive quantitative assessments that capture all of the aspects of climate change, water use, and land use that we care about.

Nevertheless, we are able to make some qualitative overall assessments. It is likely that biofuels produced from crops (e.g., ethanol from corn) using conventional agricultural practices will not mitigate the impacts of climate change, and will exacerbate stresses on water supplies, water quality, and land use, compared with petroleum fuels. To avoid these problems, biofuel feedstocks will have to be grown on land that has no alternative commercial use and no potential alternative ecological benefits, in areas with ample rainfall or groundwater, and with little or no inputs of fertilizers, chemicals, and fossil fuels. Although this can be done experimentally at small scales, it is not clear that it can be done economically and sustainably at large scales. We can conclude, then, that the development of sustainable biofuels depends not only on technological progress in growing feedstocks and producing fuels, but also on developing the policies, regulations, and incentives that direct commercial biofuel development in socially and environmentally beneficial ways. ■

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