Essay

Biofuels and Biodiversity: Principles for Creating Better Policies for Biofuel Production

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Abstract: *Biofuels are a new priority in efforts to reduce dependence on fossil fuels; nevertheless, the rapid increase in production of biofuel feedstock may threaten biodiversity. There are general principles that should be used in developing guidelines for certifying biodiversity-friendly biofuels. First, biofuel feedstocks should be grown with environmentally safe and biodiversity-friendly agricultural practices. The sustainability of any biofuel feedstock depends on good growing practices and sound environmental practices throughout the fuel-production life cycle. Second, the ecological footprint of a biofuel, in terms of the land area needed to grow sufficient quantities of the feedstock, should be minimized. The best alternatives appear to be fuels of the future, especially fuels derived from microalgae. Third, biofuels that can sequester carbon or that have a negative or zero carbon balance when viewed over the entire production life cycle should be given high priority. Corn-based ethanol is the worst among the alternatives that are available at present, although this is the biofuel that is most advanced for commercial production in the United States. We urge aggressive pursuit of alternatives to corn as a biofuel feedstock. Conservation biologists can significantly broaden and deepen efforts to develop sustainable fuels by playing active roles in pursuing research on biodiversity-friendly biofuel production practices and by helping define biodiversity-friendly biofuel certification standards.*

Keywords: biodiversity-friendly biofuels, biofuels, ecological footprint, feedstock, microalgae

Biocombustibles y Biodiversidad: Principios para la Creación de Mejores Políticas para la Producción de Biocombustible

Resumen: *Los biocombustibles son una nueva prioridad en los esfuerzos para reducir la dependencia en combustibles fósiles. Sin embargo, el rápido incremento en la producción de materias primas para los biocombustibles puede amenazar a la biodiversidad. Hay principios generales que deberían ser considerados para el desarrollo de directrices para la certificación de biocombustibles amigables con la biodiversidad. Primero, las materias primas para los biocombustibes deberían ser cultivados con prácticas agrícolas seguras ambientalmente y amigables con la biodiversidad. La sustentabilidad de cualquier materia prima para biocombustibles depende de las buenas prácticas de cultivos y de prácticas ambientales sanas a lo largo del ciclo de vida de la producción de combustible. Segundo, la huella ecológica de un biocombustible, en términos de la superficie requerida para producir cantidades suficientes de material prima, debe ser minimizada. Las mejores alternativas parecen ser combustibles del futuro, especialmente combustibles derivados de microalgas. Tercero, los biocombustibles que pueden secuestrar carbono o que tienen balances de carbono negativos o neutros, cuando vistos en el contexto de todo el ciclo de vida de producción, deben recibir alta prioridad. El etanol a base de maíz es la peor de las alternativas disponibles actualmente, aunque es el biocombustible más avanzado para producción comercial en los Estados Unidos. Instamos a la búsqueda de alternativas al maíz como materia prima para biocombustibles. Los biólogos de la conservación pueden ampliar y profundizar significativamente los esfuerzos para desarrollar combustibles sustentables al jugar papeles activos en la*

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investigación sobre prácticas para la producción de biocombustibles amigables con la biodiversidad y al ayudar a definir estándares de certificación para biocombustibles amigables con la biodiversidad.

Palabras Clave: biocombustibles, biocombustibles amigables con la biodiversidad, huella ecológica, materia prima, microalgas

Introduction

Biofuels are heralded by environmentalists and government leaders as the most promising renewable alternatives to achieve the goals of reducing our dependence on fossil fuels and lowering CO_2 emissions (e.g., Farrell et al. 2006; Ragauskas et al. 2006), and in some cases, of supporting local agriculture and developing economies (e.g., Goldemberg 2007). Coupled with effective energy conservation measures, increased biofuel use has the potential to slow the effects of global climate change, which has led to a proliferation of biofuel production and legislation. Policy makers at all levels are rushing to stimulate rapid expansion of biofuels, and most biofuel legislation requires benchmark percentages of ethanol or biodiesel be sold in coming years (e.g., U.S. Energy Policy Act of 2005 (Pub. L. 109–058) included a renewable fuel standard requiring use of 7.5 billion gallons of biofuels by 2012). Nevertheless, to achieve environmental goals and avoid harm to biodiversity, policies also need to outline environmental standards for biofuel production. Currently, there are few or no legislative provisions that delineate principles and standards to follow to protect the environment.

Despite its many advantages over petroleum-based fuels, biofuel production and use may result in significant negative consequences for biodiversity through pollution, soil degradation, and climate impacts from their cultivation, transportation, refining, and burning (Cook et al. 1991; Worldwatch Institute 2006). Heavy water use in cultivation and refining may also have a negative impact on biodiversity (Berndes 2002; NAS 2007). Most significantly, expansion of agricultural lands for biofuels into sensitive and less-developed areas would decrease availability of habitats suitable for many species and reduce the ecosystem services offered by more complex ecological systems. This has become evident as expansion of corn ethanol production since 2005 has threatened lands enrolled in the U.S. Department of Agriculture Conservation Reserve Program (Marshall 2007), and as expansion of palm oil plantations comes at the expense of natural habitats in Malaysia (Conservation in Practice 2007). We are particularly concerned that the primary emphasis today is on land- and water-hungry biofuel feedstocks. Poorer choices among feedstocks and cultivation or refining practices can undermine environmental goals of biodiversity conservation and natural resource sustainability.

We outline 3 general principles that can guide development of biodiversity-friendly biofuel policies and recommend promising feedstock choices and desirable practices in biofuel production. To date, decisions regarding biofuel production have been driven primarily by economic and political factors, with substantial subsidies going toward development of corn ethanol, in particular. Few policies have been drafted that include provisions to protect biodiversity and ecosystem health (with a notable exception of the U.S. Advanced Clean Fuels Act of 2007). We argue, however, that the central goals of any biofuel policy also must minimize risks to biodiversity and to our climate. Conservation biologists should play a major role in guiding the creation and implementation of policies that ensure alternative fuel targets are met without a loss in biodiversity, and moreover, in helping to establish practices that improve biodiversity and ecosystem health. Conservationists can contribute by applying their expertise toward defining biofuel certification standards and by promoting research agendas on strategies to enhance prospects for biodiversity. By focusing on research questions such as how to produce biofuels without degrading natural habitats, how to manage production lands for both economic and ecological sustainability, and how biofuel cultivation might be used to restore severely degraded lands, conservation biologists can influence biofuel policy in meaningful and powerful ways.

Investigating and Promoting Biodiversity-Friendly Practices for Biofuels

There are a number of avenues for research and education that conservationists can explore to support the case for developing biodiversity-friendly biofuels. Three general principles should guide investigative efforts to strengthen biofuel practices and policies: (1) promote sustainable and low-impact feedstocks with a small ecological footprint, (2) maintain native and essential food crop habitats, and, at a minimum, (3) require net carbon-neutral biofuels.

Promote Sustainable and Low-Impact Feedstocks

Biofuels are a sustainable source of energy only if feedstocks are grown sustainably: feedstocks should be cultivated with biodiversity-friendly practices, and biofuels with the smallest ecological footprints should be promoted. Most biofuel research has focused on attaining costs comparable to petroleum, and researchers assumed large-scale agribusinesses for the energy crop (heavy energy inputs, high pesticide, fertilizer, and water use) would be created (e.g., U.S. Department of Energy Renewable Energy Biomass Program). Currently, more than 90% of biofuels produced and used in the United States come from corn, which is grown with some of the highest fertilizer and pesticide inputs of any major U.S. crop (USDA NASS 2007) and the highest inputs per acre of any biofuel crop (NAS 2007). The high nitrogen inputs from crops, particularly corn, in the Mississippi watershed are implicated in the expansion of the hypoxic zone in the Gulf of Mexico (Rabelais et al. 2002; NAS 2007). Adopting the large-scale agribusiness model for most biofuels would result in greater levels of water use, nitrogen- and pesticide-related pollution, and CO_2 emissions; reduced land area for biodiversity and critical food-crop production; and associated health risks for the farmers and other citizens.

What is needed is an explicit calculation of the ecological footprint caused by large-scale cultivation of a given biofuel energy crop, that includes different modes of processing the feedstock into a liquid fuel. Biofuel ecological footprints are a function of many factors. Energy efficiency or net energy balance (energy output:energy input) over the life cycle of the biofuel combined with its fuel yield per hectare will affect the ecological footprint. All of these variables affect the amount of land needed to grow sufficient quantities of a biofuel to replace petroleum-based fuels to a substantial extent and to meet legislated benchmarks. Greenhouse gas emissions over the life cycle of the product, relative levels of water, fertilizer, and pesticide use, and amount of energy required to cultivate and refine the feedstock all contribute to the ecological footprint of a biofuel. We gathered data and created rough estimates of these variables for today's leading biofuel feedstocks (Table 1). Although some of the values are represented by only one or a few studies, and local growing conditions and agricultural practice will influence strongly the impacts of any biofuel crop, the relative magnitude or qualitative ranks suggest probable long-term differences in ecological impacts, and therefore the overall sustainability of different biofuel feedstocks.

Biofuels that require few inputs, use native species, and emphasize perennial species, particularly in polyculture or multiyear rotations, will be more biodiversity-friendly than energy-intensive monocultures of annual crops. Polyculture methods, which could increase the value of biofuel crops for biodiversity while decreasing pest and soil fertility problems, have been explored only recently (Tilman et al. 2006) and could be an important avenue for new research. Conservation biologists can contribute to this research by investigating the biodiversity costs and benefits of cultivating a larger area of land in polyculture or seminatural habitat compared with cultivating a smaller area of land in monoculture. The answer to this question may depend in part on whether a biofuel crop can produce high-energy yields per hectare under low-input methods. For example, switchgrass (*Panicum virgatum*) generally can be grown with much lower fertilizer inputs than other crops, particularly corn (Graham et al. 1995; Parrish & Fike 2005). Switchgrass has been explored far more extensively than most feedstocks, which has led to improvements in yield and energy extraction and development of site-specific agricultural best practices (Parrish & Fike 2005). As with other perennial crops, switchgrass sequesters carbon below ground, resulting in a negative greenhouse-gas balance (Adler et al. 2007; Table 1). Nevertheless, switchgrass is being developed as a high-yield monoculture variety and therefore is likely to require greater fertilizer, pesticide, and water inputs than biofuel crops grown in polycultures, particularly those composed of native species.

We should continue to explore the potential for native, perennial prairie grasses (in addition to switchgrass) to serve as biodiversity-friendly feedstock. In a test project Tilman and colleagues (2006) grew a diversity of native prairie species on a site with degraded soils, used little or no fertilizer or pesticide inputs, irrigated only in the first year to facilitate plant establishment, and yet obtained estimated fuel yields per hectare comparable to those of corn at a vastly higher conversion efficiency (roughly 5.44 vs. 1.25, respectively; Table 1). The native prairie species also sequester carbon. Using native grassland systems as a biofuel feedstock also has a number of potential biodiversity benefits that should exceed those of monocrop options. Such systems would serve as habitat for native species, and cropping may increase soil fertility over time and reduce erosion rates compared with traditional crops on tilled prairie (Tilman et al. 2006). Finally, because native prairie supports a diversity of pollinators, expansion of such systems adjacent to crops requiring pollinator services could provide an additional ecosystem service (Hill 2007).

Biofuels made from lignocellulosic biomass come from perennial species or wood, and crop residues may prove to be more ecologically friendly than grain and grass feedstocks. Poplar and willow have been grown successfully with municipal-waste fertilizers and irrigated with municipal or industrial wastewater, thus decreasing waste streams while achieving inputs needed for high yields (Powlson et al. 2005). Nevertheless, the higher yielding, genetically modified varieties require more inputs and thus could pose environmental and genetic risks unless grown sustainably and with care to minimize risk to native species. Because biomass plantations typically cannot support wildlife and provide economically profitable timber returns, this option serves biodiversity conservation goals far better when it involves restoring degraded lands to plantations or uses cellulosic debris from

Table 1. Comparison of estimated feedstock efficiencies, environmental impacts, and land-use requirements to produce 50% of U.S. demand for transportation fuels from various biofuel crops.

Biofuel crop	Energy conversion efficiency[a]	GHG emissions[b] (kg CO2/MJ)	Water use[c]	Fertilizer use[d]	Pesticide use[e]	Energy inputs[f]	Fuel yield[g] (l/ha)	Land area needed to meet 50% of U.S. transportation fuel demands[h] (million ha)	(% U.S. cropland)	Additional considerations[i]	Sources[j]
Grasses → ethanol											
Corn	1.1–1.25	81–85	high	high	high	high	1135–1900	290–485	157–262	A, F	3, 5
Sugar cane	8–10.2	4–12	high	high	med	med	5300–6500	85–105	46–57	A	4,7,12
Switch grass	1.8–4.4	−24	med-low	low	low	low	2750–5000	110–200	60–108	P, N, R	1,5
Native prairie grasses	est. 5.44	−88	low	low	low	low	est. 940	585	316	P, N, W, Expt	5,11
Woody biomass → ethanol/synfuel											
Poplar & willow spp.	10	−24 to 11	low-med	low-med	low	low	5500–9000	60–100	32–54	P, W	1,10
Fischer-Tropsch (2nd generation fuel)	18–64	−24 to 11	low-med	low-med	low	low	30,000–50,000	11–18	6–10	P, W	1
Residues → biodiesel/ethanol											
Wood residues	20–40	—	med	low	low	low	1150–2000	275–475	150–250	P, W	8, 10
Corn stover	5–11	81	med	high	high	low	0.25–0.3 l/kg	—	—	S	1, 8
Wheat straw	2–5	—	low	med	med	low	0.3–0.5 l/kg	—	—	S	8, 10
Oil crops → biodiesel											
Soybeans	1.9–6	49	high	low-med	med	med-low	225–350	330–450	180–240	A, D, F	2,5
Rapeseed or canola	1.8–4.4	37	high	med	med	med-low	2700	55	30	A	2,6
Oil palm	9	51	high	med	low	low	4760	34	18	P, D	2
Microalgae → biodiesel	—	−183	med	low	low	high	49,700–108,800	1.5–3.2	1.1–1.7	Expt	2,9

[a] *Conversion efficiency: energy output/fossil energy input. The conversion efficiency for gasoline is 0.83–0.85, whereas that for diesel is 0.8–0.94.*

[b] *GHG: Greenhouse gas emissions over biofuel life cycle should be compared to those of gasoline (94 kgCO2e/MJ fuel) for ethanol products, or diesel (83 kgCO2e/MJ fuel) for biodiesel products.*

[c] *Water use: includes both water needed to grow the biofuel and used in the refining process.*

[d] *Fertilizer use: high, majority (>85% farms) apply high amount; med, either lower amount applied or fewer farms using high fertilizer inputs; low, amount applied low or none.*

[e] *Pesticide use: includes insecticides, herbicides fungicides, and other toxins to fight pest infestations: high, majority (>85% farms) apply high amount; med, lower amount applied; low, amount applied very low or none.*

[f] *Energy inputs: include energy needed to run mechanized farm equipment, transport feedstock and fuels, refine fuels.*

[g] *Yield is liters of ethanol or biodiesel obtained per hectare. Current efficiencies are given for grasses and oil crops, whereas others generally represent estimates based on predicted efficiencies and do not represent verified commercial values.*

[h] *Assumes annual U.S. transportation fuel use is approximately 550 billion liters gasoline/yr and approximately 160 billion liters diesel/yr, based on 2005 consumption levels (EIA 2006). Comparisons: land area in hecteres needed to produce sufficient ethanol to replace gasoline or biodiesel to replace diesel for each biofuel crop. Assumes total U.S. cropland area is approximately 185 million ha.*

[i] *Additional factors that may enhance or detract from the sustainability or biodiversity supportive potential of a given biofuel.*

A, annual; P, perennial; N, native spp.; R, potentially pest resistant; W, provides wildlife habitat; Expt, experimental trial(s) only, not yet conducted on demonstration scale; S, use may entail soil effects, including lower carbon sequestration and erosion control; F, may compete with food production; D, production of this biofuel is already contributing to deforestation in species-rich habitats.

[j] *Sources for conversion efficiency, GHG emissions, and fuel yield, as well as additional information about crops: 1, Adler et al. 2007; 2, Chisti 2007; 3, Farrell et al. 2006; 4, Goldemberg 2007; 5, Hill et al. 2006; 6, IEA 2006; 7, Macedo et al. 2004; 8, Perlack et al. 2004; 9, Sheehan et al. 1998; 10, Sims et al. 2006; 11, Tilman et al. 2006; 12, Worldwatch Institute 2006. Land area requirements estimated by authors.*

production forests, forest health projects, or restoration sites, rather than converting forested lands to such uses. The suitability of woody biomass also depends on the degree to which native species are used and trees are grown sustainably. There are technical obstacles to lignocellulosic biomass conversion to ethanol that have yet to be solved before such biofuels can be produced at commercial scales. Yet, research that could define the conditions under which biofuels derived from woody biomass are biodiversity-friendly is needed.

Junginger et al. (2006) speculate that almost one-quarter of current energy demand can be met by using organic waste and residues from agriculture and forestry. Nevertheless, other researchers (e.g., Lal 2006) point out the critical role crop residues often play in maintaining soil fertility and reducing erosion. Indeed, retaining crop residues on site and in-planting among these residues are elements of conservation tillage practices aimed at increasing agricultural sustainability. Because soil tilling increases soil erosion rates, many are trying to promote nontilling techniques. Crop residues can reduce erosion from rain and wind, and suppress weed growth. Conservation tillage is currently practiced on only 10% of arable lands, yet if practiced more broadly could drastically decrease erosion rates and, in most cases, enhance soil fertility (Lal 2006; Scherr & McNeeley 2007).

Crop yields, for energy or for food, are intimately tied to the health of the soils. The various proposed biofuel crops differ greatly in soil fertility and fertilizer requirements, and in types of soil management or conservation practices compatible with high yields. For example, switchgrass appears to obtain nitrogen from soils more efficiently than many other tested species (including corn and other grasses; Parrish & Fike 2005). Tilman et al. (2006) report minimal fertilizer inputs were required in their system of mixed native prairie grasses grown on degraded soils. In contrast, corn (and to a lesser extent soy) is grown with substantial fertilizer inputs (USDA NASS 2007), often resulting in high nitrogen runoff into surrounding and distant waterways and increased greenhouse gas emissions (Powlson et al. 2005; Hill et al. 2006).

Practices explored in the ecoagricultural literature provide many positive examples that can be adapted to any biofuel production effort (e.g., Scherr & McNeeley 2007). Ecoagricultural practices are characterized by the use of soil, water, pest, and energy management strategies that are sustainable; the recovery of degraded lands rather than expansion into intact natural habitats; and the use of cropping systems that maximize coexistence with a diversity of wild species. Conservation biologists should research applications of ecoagricultural principles and ecologically sound agricultural practices to develop region-specific standards or best practices for obtaining highest yields with the least environmental impact.

Maintain Native and Essential Food-Crop Habitats

Biofuels will be biodiversity-friendly only if their use does not intensify agricultural impacts, expand agricultural conversion of native habitats or displace cropland necessary for meeting human nutritional demands. Unfortunately, at current energy-extraction efficiencies, energy crops will need to be grown on a massive spatial scale to replace even half of U.S. transportation fuel demands (Table 1). The spatial scale of biofuel crop production has enormous subsequent impacts on biodiversity. Currently, 20–50% of the land area in a majority of terrestrial biomes has been converted to food production for a growing global population (Millennium Ecosystem Assessment 2005). This global loss of habitat is magnified by increasingly large areas being cleared to meet the demand for biofuels, converting biodiverse lands into monocultures. In Indonesia and Malaysia, extensive tracts of tropical rainforest (including protected areas) have been cleared to create oil-palm plantations for biodiesel (Hensen 2005; Dennis & Colfer 2006). In the U.S. Midwest, corn acreage is expanding rapidly to provide fodder for ethanol production (U.S. EIA 2006; Marshall 2007). In Brazil there is substantial pressure to expand the coastal fields of sugar cane and convert additional cerrado habitats to soybean or sugar cane plantations, particularly following the recent Brazil–United States agreement to increase ethanol export to the United States (U.S. State Department 17 March 2007). Conversion of cerrado habitats and amazonian rainforests has accelerated in recent decades, and there has been a concurrent expansion of soy plantations (Nepstad et al. 2006).

Pressure to increase the use of woody biomass for biofuel production could lead to conversion of forests to tree plantations (with short-rotation tree species being most profitable for biofuel production, especially poplar (*Populus* spp.) and willows (*Salix* spp.). In contrast, if the land is already cleared, tree energy crops may enhance biodiversity. Indeed, if biofuel production from woody biomass becomes profitable, it might serve to motivate land restoration to avoid conversion of native habitats.

Meeting current global demand for petroleum via current-generation biofuels would require a doubling of the human share of net primary productivity, which would threaten species and habitats with extinction and sharply decrease global food security (Junginger et al. 2006). Thus, many look to high-efficiency extraction of hydrocarbons from lignocellulosic biomass as a necessary precondition to successful use of biofuels (e.g., EEA 2006), whereas others point to microalgal biofuel production as the ultimately most efficient biofuel, both in terms of land use and energy conversion (e.g., Chisti 2007). Although the technical capacity to create large volumes of biofuels from microalgae have not yet been achieved (Ragauskas et al. 2006), we find this by far the most promising type of alternative, deserving of far greater attention and research.

Among energy crops for which commercial-scale refining or demonstration projects are established, cellulosic ethanol and some biodiesels have shown strong energy returns, whereas much-less-developed alternative fuels derived from microalgae have astounding potential for high energy returns (Table 1). Cellulosic ethanol is derived from grasses, crop and wood residues, and fast-growing trees (such as poplar or willows) and typically yields >10 times as much energy as is needed to produce the fuel (Powlson et al. 2005). Similarly, biodiesels have a high carbon content and return 2–6 times the energy used in production (Powlson et al. 2005; Hill et al. 2006). With second-generation fuel-refining technology (e.g., Fisher–Tropsch processes), cellulosic ethanol is expected to have much higher yields and consequently could have a much lower ecological footprint (Dien et al. 2003; Gray 2007; Table 1).

The use of microalgae to produce biomass of high energy content has enormous potential for much higher energy yields and a much smaller ecological footprint (Sheehan et al. 1998; Kalscheuer et al. 2006; Chisti 2007; Table 1). At present, microalgal biofuels are 4–10 times as expensive to produce as petroleum-derived fuels or other biodiesels (Chisti 2007). Nevertheless, only algal or microbial biofuels could be produced with a truly small ecological footprint because the space requirements for conventional crops or tree crops are 1–2 orders of magnitude greater (Table 1). Even when grown in the least space-efficient manner (in large open ponds), only 200,000 ha would be needed to produce 1 quadrillion BTU from microalgae biodiesel (Sheehan et al. 1998), which is vastly less than the land area needed to produce a similar quantity of corn-derived ethanol (approximately 40 million ha) or soy biodiesel (approximately 20 million ha). If microalgae were to reach its full potential, dedicating just 1.1% of U.S. cropland to microalgal production could replace half of the country's transportation fuel needs (Chisti 2007; Table 1). Furthermore, many of the most promising species are diatoms and green algae that tolerate brackish or salt water and thus can be grown without use of increasingly scarce freshwater resources (Sheehan et al. 1998). Given the potential for much higher energy returns with microalgae, relative to other biofuels, this is an area that should be pursued actively.

In contrast to these higher potential yields, most estimates of energy returns from corn-derived ethanol show only a slight benefit, with a net energy balance of only 25%, or 1.25 times the energy needed to produce the fuel, because of the typically high inputs needed to grow the crop and the relatively low energy yield from this feedstock (Farrell et al. 2006; Hill et al. 2006; Table 1). Thus, the current push to increase use of biofuels primarily through corn-based ethanol is clearly employing the least beneficial alternative fuel.

Finally, biofuels may compete with arable land for growing food. In developing countries, this trade-off could result in social and economic problems. In the United States increased corn prices due to ethanol mandates have resulted in widespread concern about impacts on livestock and other agricultural sectors, as well as on consumers (Marshall 2007).

Require Net Carbon-Neutral Biofuels

Given the urgent need to radically decrease greenhouse gas emissions, biofuels with the lowest CO_2 emissions should be pursued most aggressively. One of the primary reasons to support expanded biofuel production is that such fuels should be less polluting and release fewer greenhouse gases than petroleum-based fuels. Nearly all proposed biofuels, with the exception of corn-based ethanol, show strong potential to reduce pollution and cut CO_2 outputs (Powlson et al. 2005; Farrell et al. 2006; Table 1).

Many proponents tout biofuels as CO_2-neutral because the plants absorb CO_2 as they grow, but this view fails to consider energy inputs required to grow, harvest, transport, process, and distribute fuels, and the release of CO_2 on burning of the biofuel. Consequently, the degree to which any biofuels may decrease CO_2 emissions relative to gasoline depends on production and refining methods (Powlson et al. 2005; Turner et al. 2007). In the United States corn-based ethanol is grown in mass monocultures with very high inputs. When it is refined in a coal-fired plant, it is at best only marginally better than gasoline in terms of CO_2 emissions (e.g., Farrell et al. 2006; Hill et al. 2006; Turner et al. 2007). The energy source that is used to process a feedstock into a fuel is particularly critical; biofuels made in refineries with a renewable energy source should be promoted and given higher certification rankings.

Development of biofuels may increase CO_2 emissions significantly if forested lands are cleared for energy crops (Giampietro et al. 1997; Junginger et al. 2006). For example, as Brazilian forests were converted first to pastures and then to sugar cane plantations, the soil organic carbon storage was depleted by >40% (Silveira et al. 2000). Overall, forest conversion accounted for 75% of Brazil's greenhouse gas emissions from 1990 to 1994 (Macedo et al. 2004). Similarly, oil-palm plantations have spread extensively in Malaysia, Indonesia, and Thailand, replacing tropical forest habitats and releasing stored carbon as these forests are cleared and soils exposed. If oil-palm plantations are sited on deep peat soils, CO_2 emissions from the soil can be substantial (Worldwatch Institute 2006). Thus, the potential for biofuel production to ameliorate climate warming depends on what kinds of lands are put under biofuel crop cultivation (Smeets et al. 2005; Marshall 2007). Conservation biologists can help by identifying land that should not be cultivated and land of particular promise for restoration projects that include a biofuel-cropping component.

Results of research on ethanol derived from prairie grasses (Tilman et al. 2006) and from cellulosic woody biomass (e.g., Graham et al. 1995; Perlack et al. 2005) suggest that these energy crops are at least CO_2-neutral, and when grown with minimal inputs would provide a net reduction in CO_2 emissions because carbon is stored below ground in perennial species (Table 1). Soy-derived biodiesel also generally outperforms corn-derived ethanol (Turner et al. 2007). Production of microalgae requires efficient and high CO_2 use, which should drastically reduce CO_2 emissions, but no estimates of likely emissions exist. Some industrial projects use energy coproduction methods that connect algal growth chambers to flue exhausts from power plants, which has the advantage of mitigating CO_2 emissions on site (Chisti 2007). All these alternatives deserve further research and development.

Energy-conservation measures in lowering greenhouse gas emissions are also important. In the transportation sector many policies can reduce CO_2 emissions, including improvements in the Corporate Average Fuel Economy (CAFE) standards for automobiles and trucks, clean-car emissions standards, and greater investment in mass transit systems. Some policies, such as those that reduce destructive land uses by concentrating development in less ecologically sensitive areas, are more advantageous to biodiversity. Reductions in emissions through carbon-neutral energy sources (such as wind, solar, and geothermal energy, and perhaps advanced nuclear energy projects) can reduce emissions for residential, commercial, and industrial energy use. Pacala and Socolow (2004) identified a number of "climate stablization wedges," including replacing fossil fuels with biomass fuels, that together could serve to reduce emissions enough to avert the more deleterious effects of climate warming, but which are unlikely to cut emissions sufficiently on their own. Certainly, we will need to use many strategies to meet the challenges from global climate change.

Conclusion

Biofuels are exciting emerging alternatives to petroleum-based fuels and may serve as an important piece of the carbon-emissions-reduction puzzle. Their use alone will not bring about the CO_2 emission reductions necessary to avert catastrophic climate change, and they cannot replace fossil fuels entirely. Furthermore, certain feedstock-production practices can in fact cause great harm to the land, soils, water, and climate. Because biofuels have environmental costs, policies promoting them need to include considerable guidance to encourage best practices in feedstock production and refining practices. Toward this end, we offer 12 general principles that should be included in such policies in Table 2. We urgently need certification standards that are tiered to reflect differences in the ecological compatibility of growing practices and the environmental effects of different potential feedstocks (e.g., Turner et al. 2007). Conservation biologists should raise awareness of where biofuel expansion is creating negative consequences for ecosystem and human health and actively research methods that can be used to foster biodiversity-friendly biofuels. Furthermore, conservation biologists should push for certification criteria that have stringent environmental standards and that include prior land use as a particularly stringent criterion for a high ranking.

Biofuels will only be beneficial if they are cultivated under sustainable, biodiversity-friendly practices. Importantly, all the factors we considered here suggest that corn-based ethanol is the worst alternative among leading potential biofuels. Although corn-based ethanol may be a useful short-term strategy to gain some of the benefits of biofuels because of its extreme dominance in the United States, we believe it is critical to move beyond corn as swiftly as possible to alternate feedstocks that will be far more effective at addressing environmental concerns. Furthermore, biofuels may become more useful as technical breakthroughs enable greater efficiencies of energy extraction, particularly from very compact biofuels, such as microalgae, which require little land area. Conservation biologists should encourage efforts to develop these alternatives. A complete portfolio of green energy strategies includes efforts that decrease energy demand and promote alternative energy sources that produce little or no CO_2 and do not lead to clearing of natural habitats.

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Table 2. Policy recommendations to promote sustainably grown, biodiversity-friendly biofuels.*

1. Evaluate the entire life cycle of biofuel production, use, and waste disposal to calculate the ecological footprint of any biofuel.
2. Require that the sustainability of biofuel feedstock production be assessed, and promote only biofuels that can be produced sustainably.
3. Select species with high conversion efficiencies to minimize land area needed to produce biofuels. This will generally include lignocellulosic feedstocks for next-generation biofuel production and, most promisingly, microalgae.
4. Encourage restoration or reclamation of degraded areas for biofuel cultivation, wherever appropriate.
5. Prohibit clearing of natural areas to increase area under cultivation.
6. Ensure that feedstock production does not adversely affect ecosystem processes and sensitive habitats and investigate production methods that may enhance ecosystem processes over time.
7. Promote use of energy crops that can be grown with low fertilizer, pesticide, and energy inputs in most settings.
8. Promote use of native and perennial species.
9. Prohibit use of species that can become invasive.
10. Promote polyculture to reduce soil depletion and create biofuel cropping systems that can be used by a greater diversity of wild species.
11. Employ conservation tillage or other appropriate techniques to conserve soils.
12. Measure the greenhouse gas emissions over the biofuel production and use life cycle, and promote only those biofuels that are based on feedstocks and refining methods that are net carbon neutral or that sequester carbon.

**Each is also an area needing additional research to help identify best practices, and each area can be expanded to detail distinct tiers for certification standards.*

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