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Biofuels and sustainability

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Interest in liquid biofuels production and use has increased worldwide as part of government policies to address the growing scarcity and riskiness of petroleum use, and, at least in theory, to help mitigate adverse global climate change. The existing biofuels markets are dominated by U.S. ethanol production based on cornstarch, Brazilian ethanol production based on sugarcane, and European biodiesel production based on rapeseed oil. Other promising efforts have included programs to shift toward the production and use of biofuels based on residues and waste materials from the agricultural and forestry sectors, and perennial grasses, such as switchgrass and miscanthus—so-called cellulosic ethanol. This article reviews these efforts and the recent literature in the context of ecological economics and sustainability science. Several common dimensions for sustainable biofuels are discussed: scale (resource assessment, land availability, and land use practices); efficiency (economic and energy); equity (geographic distribution of resources and the "food versus fuel" debate); socio-economic issues; and environmental effects and emissions. Recent proposals have been made for the development of sustainable biofuels criteria, culminating in standards released in Sweden in 2008 and a draft report from the international Roundtable on Sustainable Biofuels. These criteria hold promise for accelerating a shift away from unsustainable biofuels based on grain, such as corn, and toward possible sustainable feedstock and production practices that may be able to meet a variety of social, economic, and environmental sustainability criteria.

Keywords: biofuels; biomass energy; carbon dioxide; cellulosic ethanol; sustainability

Introduction

Biofuels have become a popular way to use renewable biomass energy and have emerged as a potentially major alterative to gasoline and diesel transportation fuels derived from petroleum. Interest has been growing in the large-scale application of biofuels to address the twin global challenges of global climate change, and shifting away from increasingly scarce and environmentally and politically risky petroleum supplies.[1–9]

At least in theory, biofuels can play a key role in solving these problems in many nations, as long as the biomass sources are grown, converted, and used sustainably. However, historically speaking, the biofuels industry has largely ignored sustainability criteria and consequently has been the source of considerable controversy in North America, Europe, and Southeast Asia.[10–12] Indeed, a few notable analysts have suggested that biofuels development to date has been uneconomical, energy-inefficient, and environmentally and socially harmful, whether developed in the United States, Brazil, Europe, Southeast Asia, or elsewhere.[12,13] Even so, production of biofuels, such as ethanol and biodiesel, has been rapidly expanding in recent years, a trend that is expected to continue given the global interest in low or no carbon fuels and alternatives to petroleum (although this will depend in part on future oil prices). Many nations are promoting advanced, "second-generation" biofuels, such as cellulosic ethanol, as are the United Nations and World Bank, as one possible solution to the climate problem, but with some significant startup risks.[14,15] Thus, an integrated assessment of the sustainability of existing and future biofuels systems is timely in the context of ecological economics, which is the purpose of this review.

Four principal fuels can be manufactured from biomass: ethanol, methanol, biodiesel, and hydrogen—although other fuels (e.g., biobutanol and dimethyl ether) can also be made from biomass.[16] Among these fuels, the leading commercial options in recent years have been ethanol manufactured from cornstarch in the United States, ethanol made from sugarcane in Brazil, and biodiesel produced primarily from rapeseed oil in Germany and France.[9] This article will focus on ethanol and biodiesel only, given their dominance in current transportation energy systems and corporate plans over the next decade. The production of ethanol from the cellulosic portion of biomass sources (or more aptly, and hereafter, referring to cellulose *and* hemicellulose), such as wood; perennial grasses; and agricultural, forestry, and municipal wastes and residues, has been highly touted over the last few years but will require at least another decade to establish as a significant share of the biofuels mix.[17]

Ethanol has been used in automobiles since the late 1800s, and initially a much larger role for it was envisioned before the domestic petroleum industry developed. It has an energy density of 24.0 MJ/liter, which is only around 68–75% the density of gasoline at 32–35 MJ/liter.[18,19] Ethanol is currently used as a gasoline additive in most U.S. states. It has largely replaced methyl tertiary butyl ether (MTBE) in most states in the last 6 years as a gasoline additive and oxygenate to reduce air pollution. Although the energy density of ethanol is lower than gasoline, its octane rating is 35–40% higher and the fuel can improve thermal efficiency (and in theory engine performance) when compared with pure gasoline. However, since most automobile engines are not optimized to run on pure ethanol or high ethanol/gasoline blends, this potential advantage remains to be exploited. Cornstarch is the current source of over 95% of the ethanol produced for use in U.S. automobiles, mostly for use in 10% blends with gasoline (E10). While the economics of ethanol are controversial, its production capacity would be nowhere near its current level of 38 billion liters per year and about 6% of U.S. motor vehicle fuel use if not for large government subsidies.[20]

All car engines in the United States that have been produced after 1988 can run on ethanol-alcohol E10 blends without problem, and in most cases up to E20. Currently, over seven million cars in the United States have engines that can use an E85 fuel blend,[21] and most engines that do not can be modified for a few thousand dollars. In many automobiles, however, ethanol use may result in corrosion, deterioration, and breakdown of some metal and plastic components, and rubber and cork gaskets.

Biodiesel fuel production requires that alkyl esters first be extracted from a feedstock, such as animal fats or vegetable oils (soybean, rapeseed, sunflower, palm, waste vegetable oil, etc.), and transesterified to produce fuel. The purpose of transesterification is to lower the oil's viscosity. Biodeisel also has a long history, dating back to 1885 when Rudolf Diesel built the first diesel engine with the intention of running it on vegetative sources. This fuel is biodegradable and nontoxic, with an energy density of 33 MJ/liter.[18,19] Because of the inherent high compression of diesel engines, this fuel can be operated with 20–30% higher efficiency than comparable gasoline engines. Biodiesel development advanced in the 1920s and 1930s through the testing of a variety of feedstocks in several countries. After decades of research, the first commercial plant opened in Austria in 1989.[22] Production from rapeseed oil became popular in Europe in the 1990s, with Germany being the world's leading producer by far. Biodiesel is made from palm oil in some tropical developing countries, such as Malaysia and Indonesia, but with significant levels of rainforest loss.[23] Jatropha and pongam trees also have been proposed as feedstock in India, Pakistan, Africa, Malaysia, the Philippines, Australia, and elsewhere since they can be grown on poor soils and are drought- and pest-resistant.[14,24]

The rest of this review is organized as follows. The next section, which is the heart of the paper, considers and defines the traditional dimensions of sustainable development and ecological economics in the context of biofuels: optimal scale, e.g., resource assessment and land availability; energy and economic efficiency; equitable distribution of biofuel resources and related food supplies; socio-economic issues; and environmental effects and emissions. Each of these issues will be addressed with regard to recent research on biofuels. Following this, recent efforts toward creating sustainability criteria and standards for biofuels will be reviewed. These include criteria and mandates of the international Roundtable on Sustainable Biofuels and U.S. energy policy legislation, respectively. The paper will close with some brief conclusions and prospects for sustainable biofuels.

Sustainability and ecological economics

While there is continuing and lively debate about what differentiates ecological economics from other fields, there is a growing consensus that there are three foundational issues: the optimal or sustainable scale of the economy, economic efficiency, and equitable distribution of resources.[25–28] Sustainable development and sustainability science, in turn, are usually thought of as some combination of the "triple bottom line" of economic development, social development, and environmental/resource sustainability.[29] All of these issues, among others, are being addressed in the context of biofuels. Thus, this section will review the following dimensions for biofuels: optimal scale, efficiency, equitable distribution of biofuels, socio-economic issues, and environmental emissions and effects.

Optimal scale: resource assessment, land availability, and land use practices

Large-scale biofuels production and use was first addressed in a major way by Cook *et al.*[30] and Giampietro *et al.*[31] The latter suggested that biofuels can substitute for fossil fuels only if large-scale production is biophysically feasible, environmentally sound, and compatible with the socio-economic structure of society.[31] These considerations include land use, fresh-water availability, soil degradation, air and water pollution from crop production and biofuel refining, biodiversity loss, and labor requirements. Giampietro *et al.*[31] analyzed the potential for ethanol production from crops in temperate, tropical, and subtropical regions (grain and sugar, respectively), and biodiesel production from oilseed crops in 21 countries. The analysis also briefly considered the possibility of technological improvement in biomass conversion, as well as methanol production from woody biomass, including short-rotation woody crops.

The conclusions of Giampietro *et al.*[31] were rather pessimistic regarding the large-scale use of biofuels. In separate papers, Cook *et al.*[30] and Kheshgi *et al.*[32] reached similar conclusions. None of the 21 countries that Giampietro *et al.*[31] analyzed had adequate land or water to rely exclusively on biofuels for energy use. They found further that in developed countries a biofuels-based energy sector would absorb an excessively high portion of the labor force—from 20–40%. Finally, the authors emphasized the large environmental costs that would accompany a major expansion in biofuels production, and a potentially large loss in food production capacity.[31] If correct, large-scale use of bioenergy would not be a realistic option for addressing global climate change and oil dependence. A review of 17 studies of the future global supply of biomass energy found that land availability and crop production yield were the most critical parameters, and highly uncertain.[4] More recent papers by Giampietro and Ulgiati[33] and Giampietro *et al.*[34] found that large-scale production of biofuels would entail heavy demand for land, water, and labor, though the focus was shifted to the desirability and sustainability of such an energy transition. More work on this is contained in a new book.[35]

The original findings of Giampietro *et al.*[31] were challenged by Berndes *et al.*[1] These authors reassessed the water, labor, and land requirements for large-scale bioenergy production and used the Renewables Intensive Global Energy Scenario (RIGES) developed by Johansson *et al.*[36] They found that the earlier assumptions for biomass production yields, water use, and labor requirements were overly pessimistic and inefficient. In addition, they showed that the labor, water, and land requirements for cellulose-based electricity, methanol, and hydrogen production would be much lower than traditional agricultural row crops. Consequently, Berndes and colleagues[1] concluded that large-scale bioenergy production would be feasible with much lower factor inputs, though the output should not be expected to displace the total present commercial energy supplies, in contrast to Johansson *et al.*[37] and Hoogwijk *et al.*[5] Actual consequences of large-scale cellulosic energy crop production would depend on the location of the crops, (shifts in) land use practices, and government policies, points also made more recently and forcefully by Searchinger *et al.*[11] and Fargione *et al.*[12]

The feasibility of a large-scale biomass energy industry in the United States was addressed in great detail in an ambitious analysis sponsored by the U.S. Departments of Agriculture and Energy (USDA/DOE).[38] This study investigated the ability of the U.S. land resources to provide a 30% displacement of petroleum consumption by 2030. More specifically, a federal Biomass R&D Technical Advisory Committee set the very challenging goals for biomass to produce 5% of the nation's electric

Table 1. Potentially available net biomass energy resources that could be sustainably removed from U.S. forests on an annual basis, in 2030 (million dry tonnes per year)

Pulping liquors and wood processing mill residues	Fuel treatments to reduce fire hazards	Logging residues and site clearings	Fuelwood harvest	Urban wood residues	Total
Existing uses					
88.9	0	31.8	0	7.3	128
Unexploited uses					
7.3	54.4	0	37.2	25.4	124.3
Forest growth					
34.5	0	14.5	20.9	9.9	79.8
Total					
130.7	54.4	46.3	58.1	42.6	332.1

Unexploited resources are currently burned or left onsite, landfilled, or diverted to other products and markets; forest growth refers to the additional residues that would be expected to result from a continuation of market trends in the forest products industry; and the total quantity available does not add up to 334 million dry tonnes because of rounding.
Adapted from Perlack *et al.*[38]

power, 20% of its transportation fuels, and 25% of its chemicals by 2030. The study concluded that these goals could be met and surpassed. A total potential of 1.24 billion tonnes of biomass production per year was projected under the high-yield scenario, with 73% available on agricultural lands, though it should be emphasized that not all of this resource would be dedicated to biofuels.

Forestlands in the contiguous United States were found capable of eventually producing 334 million dry tonnes annually, or more than 2.5 times the current consumption rate of forest biomass energy resources, on a sustainable basis. The U.S. forest biomass resource projections for 2030 are shown in Table 1. The largest resource category is projected to be pulping liquors and wood-processing mill residues, which accounted for 39% of the total estimate. Overall, only about 39% of the forest-based biomass energy resource base is currently used, primarily for energy production in the pulp and paper industry, but also for firewood.

The total biomass energy resources that might be generated each year from agricultural lands, at 905 million dry tonnes per year, were projected to be more than twice that of forests. A large portion of the agricultural resource lands was determined to be capable of supporting short-rotation woody crops (e.g., willow, hybrid poplar, sweetgum, sycamore, maple, eucalyptus, loblolly pine) *if* land use changes. This projection comprised about half of the study's perennial woody crops category total, which totaled 37% of the overall agricultural lands resource potential. Roughly 34% of the total agricultural land resource was determined to be from corn grain, assuming a 50% increased crop yield as well as land use changes. About another 5% each were found to be available from wheat and soybean crops.

The USDA/DOE study made several key assumptions in their assessment: they excluded consideration of forestlands that were not currently accessible by roads or were considered environmentally sensitive; considered harvest equipment recovery limitations; did not include recoverable biomass that was projected to be needed for conventional forest products; assumed that all cropland was managed with no-till methods; assumed that the residue maintenance requirement to maintain soil sustainability was always met; assumed all manure in excess of that which can be applied on-farm for soil improvement under anticipated U.S. Environmental Protection Agency (EPA) restrictions was used for biofuels; and that all other available residues were used.[38]

Lal, in contrast, made rough estimates of just the agricultural crop residues that might be available for biofuel production in both the United States and worldwide (his U.S. estimate was comparable to that made by the research team for the USDA/DOE study led by Robert Perlack[38]), but reached much more pessimistic conclusions about the ecological risks involved.[39] These risks included the potential detrimental effects on soil carbon sequestration, soil quality maintenance, the prevention of soil erosion, and other ecosystem functions.

Johansson and Azar applied a long-term, nonlinear economic optimization model (LUCEA) to investigate the possible competition between U.S. bioenergy production and other land uses through 2100.[40] In particular, the authors tested the claim that the food–biofuel competition could be avoided by focusing biofuel production on less productive lands. Their analysis could also be considered a test of the implications of the findings of USDA/DOE, though the studies were conducted independently. Johansson and Azar[40] found that low carbon taxes would result in the most bioenergy production on cropland, with production shifting to grazing lands at higher prices, and farm gate prices for all crops and animal products increasing substantially. Thus, only because of the food–biofuel competition would the allocation of bioenergy production to lower quality lands occur.

Lynd *et al.* also addressed the question of land availability for large-scale biofuel use in the United States, but approached it differently.[41] First, they restricted their study to the future production of cellulosic ethanol. Second, they developed a simple equation to estimate biofuel land production requirements based on vehicle kilometers traveled, kilometers per liter, conversion process yield (i.e., liters of ethanol output per tonne of biomass input), and the productivity of feedstock production. Available land in excess of land required for food production was calculated as a function of gross agricultural land, minus the number of people fed times a ratio of dietary consumption per person divided by crop productivity multiplied by food conversion losses. The authors showed that net new land required to produce 380 billion liters of cellulosic ethanol per year would be robustly available, under three scenarios of productivity increases in food and biofuel production. A conservative maximum land requirement of 160 million hectares was found, assuming no increase in crop productivity.

Some tentative conclusions about the large-scale production of biofuels can be stated. While most studies conducted in the 1990s were negative about the feasibility and desirability of a large-scale biofuels industry (e.g., the work of Mario Giampietro and colleagues[31]), most studies since then have made more positive findings (e.g., the work of Göran Berndes and colleagues[1]), although there have been notable exceptions. This is based on increased knowledge of the potential for biofuels production from cellulosic materials, though commercial experience is lacking. The key parameters, all highly uncertain, include crop production yields, water use, technical conversion efficiency, soil residue maintenance requirements and practices, and land use shifts. Even so, a large-scale biofuels industry would unlikely be able to displace more than 20–30% of the petroleum-based requirement for transportation fuels in the United States.

Efficiency: energy and economic

Most of the literature on biofuels has characterized its efficiency in terms of the energy return on investment (EROI or EROEI), a concept pioneered by Charlie Hall in the 1980s. As noted by Hall *et al.*, among many others, EROI is a ratio that measures the energy that one obtains from an activity compared to the energy it took to generate that activity.[42] The numerator and denominator should be derived in the same units, although this has not always been done in practice. The reason why this issue has been hotly debated in the literature is because 75 years ago the EROI of petroleum in the United States was greater than 100:1, while today it ranges from 11:1 to 20:1 at best. Consequently, alternatives to petroleum for transportation, such as biofuels, must compete against each other in this environment of decreasing EROI that places a premium on the efficiency of energy options and investments to maintain, replace, and expand economic activity. Moreover, in a follow-up paper by Hall and colleagues, no fuel options are reasonably foreseeable which are even close to the peak EROI of petroleum.[43]

An excellent review of the ethanol EROI literature was made by Hammerschlag,[44] who considered only corn-based and cellulosic ethanol fuel. In a survey of 10 major studies, he defined EROI as:

$$r_{\mathrm{E}} = \frac{E_{\mathrm{out}}}{E_{\mathrm{in,\ nonrenewable}}}$$

where E_{out} is the energy in a specified amount of energy output and $E_{\text{in, nonrenewable}}$ is the nonrenewable energy input to the manufacturing process for the same amount of ethanol production. For corn-based ethanol (the major feedstock in the United States), the EROI with current technology ranged from 1.3:1 to 1.65:1 in five of six studies, with the notable exception of the well-known work of Pimentel and Patzek.[45] Farrell *et al.* made similar findings in their review of six studies.[46] Hill *et al.*,[47] in another contemporaneous study, calculated an EROI of 1.25:1 for corn ethanol while de Oliveira *et al.* found around 1.1:1.[48] Pimentel and colleagues,[49] in a long series of related analyses, have consistently found an EROI of less than 1:1, and have been repeatedly criticized for assuming outdated technology and improperly penalizing ethanol for its co-product energy (although other studies have had sometimes dubious assumptions, too). Pimentel *et al.* in response argued that the energy credit given to the animal feed—called distillers dried grain with solubles (DDGS), a common co-product from corn ethanol production—is too high and that the feed quality of DDGS is much lower than the feed it is supposed to replace.[49]

For cellulosic ethanol, which is currently being commercialized,[17] three of four studies reviewed by Hammerschlag found an EROI of 4.4:1 to 6.6:1,[44] with Farrell *et al.*[46] and Wu *et al.*[50] reporting values in the range of 6:1 to 11:1. Pimentel and Patzek again found a value below 1:1.[45] Here the main factor explaining the finding of the latter is their alternative assumption that cellulosic ethanol refineries would use fossil fuels rather than biomass lignin residues to generate their process energy requirements.

The other major conventional route to produce ethanol is from sugarcane, as is dominant in Brazil and India. Ethanol production in tropical countries is more efficient because of better growing conditions and the need for fewer steps required for alcohol production in the refinery.[51] Thus, the EROI is on the higher side and comparable to conservative estimates of the EROI for cellulosic ethanol. Two studies have estimated an EROI for sugarcane-based ethanol in the range of 3:1 to 10:1.[48,52] In addition, the large-scale Brazilian ethanol program has been justified as economically efficient by reducing the amount of external debt and savings in hard currency from displaced oil imports.[53]

Several similar analyses have been completed for biodiesel. For soybean-based biodiesel (the main feedstock in the United States), Hill *et al.* calculated an EROI of 3.7:1,[47] also disputing the negative findings of Pimentel and Patzek.[45] In an earlier study, Delucchi[54] has found results comparable to those of Hill and colleagues.[47] For the case of rapeseed-based biodiesel (the main feedstock in Germany and Europe), estimates of EROI have been similar but with a slightly greater range.[55]

Standard definitions of efficiency in ecological economics focus on the efficient allocation of resources. Thus while the EROI of biofuels alternatives is important, a more traditional measure of efficiency would consider the monetary cost competitiveness of biofuels. However, given the subsidies and widespread energy market failures, such as the lack of or under pricing of carbon, greenhouse gas implications of alternative biofuel production systems, long-term historical and continuing massive subsidies to fossil fuels, oil import security risks, etc., the economic efficiency argument on biofuels is much more complex. Solomon and Georgianna, for example, have shown that there can be an optimal level of subsidies to renewable energy sources that improve social welfare for such reasons over existing sources.[56] Indeed, biofuels have been heavily subsidized by federal and state governments, although this has been a source of much criticism. For example, Duke and Kammen argued that the U.S. federal subsidies for corn-based ethanol, discussed below, had not produced net social benefits by the late 1990s since production costs had not fallen enough to produce a positive net present value.[57]

Subsidies for U.S. biofuels began with support for the corn ethanol industry in 1979.[17] The most important of several support mechanisms has been a partial exemption from the federal gasoline excise tax for the fuel blend called gasohol (which usually contains a 10% component of biomass-derived ethanol). This exemption was approved as part of the 1978 Energy Tax Act. A fuel blender's tax credit and a pure alcohol fuel credit were approved in 1980. Through later years, these tax provisions were periodically renewed and altered in magnitude, with changes in one being mirrored by changes in the others. For several reasons the excise tax exemption has been the most widely used incentive (double crediting with the fuel blender's tax credit is not permitted) with total government revenue losses estimated at 16–56 times those of the other two tax credits combined. This subsidy remains of great importance to the industry. In recent years the total combined federal support for ethanol has equaled a taxpayer subsidy of $\sim$ \$4 billion per year[58]; however, this subsidy offsets an *even larger* subsidy to U.S. farmers to grow corn and the trade deficit impact of displaced oil imports.[59] The fuel tax exemption today is set at 13 cents per liter of ethanol, and while it is unlikely that corn-based ethanol would be competitive without the subsidies unless gasoline prices remain high,[60] it is difficult to determine the exact effect since most ethanol cost data are proprietary.

Cellulosic ethanol production, in contrast, has been shown by Solomon *et al.*[17,61] to be cost-competitive without subsidies under assumptions of low feedstock costs and high but arguably achievable biomass conversion efficiencies in the near future,[41] although other analyses have used different assumptions and reached the opposite conclusion.[49,62,63] Nevertheless, a recent paper has shown through a contingent valuation study of the north-central states of the United States that most consumers are willing to pay extra for this fuel, at least in the short term, to support its development.[64]

The Energy Policy Act (EPAct) of 2005 approved several major incentives to encourage in a new era of renewable fuels.[65] Cellulosic ethanol, although not yet commercial, received considerable attention from EPAct, garnering subsidies over and above that for traditional ethanol production. Even so, the most widely publicized provision of EPAct, the Renewable Fuel Standard (RFS), applies to both corn and cellulosic ethanol and will operate in the place of the now eliminated oxygenate requirement for reformulated gasoline. Implementation of the RFS by the EPA began in 2006 at 15.1 billion liters per year (which was almost met in 2005), and was scheduled to increase to 28.4 billion liters per year in 2012. Nevertheless, in light of the rapid demand growth for ethanol since 2002, EPAct has generated only a modest boost to production thus far.

The prospects for cellulosic ethanol received an even greater boost through passage of the Energy Independence and Security Act in 2007. This law revises and extends the RFS beginning in 2008 at 34 billion liters per year, up to four times that level by 2022. Of this total, no more than 56.8 billion liters per year will come from cornstarch, with the remaining 79.5 billion expected from advanced biofuels with greatly reduced greenhouse gas emissions (including biodiesel). Over 75% of the advanced biofuels total will eventually come from cellulosic materials, and this part of the mandate could be met with any combination of ethanol and other alcohols.[66]

The Brazilian biofuels program was also heavily subsidized from its start with the launching of the National Alcohol Program (Proalcool) in 1975. One of its early critics was none other than Herman Daly, although more on environmental than economic grounds. The Brazilian government offered large subsidies to the sugarcane growers and forced retail fuel stations in all towns of at least 1500 residents to install ethanol pumps. Since 1990 most of the ethanol subsidies have been phased out, and the fuel has been economically viable since 2003 and less expensive than ethanol produced in the United States or Europe.[51,67] Today, not only does Brazilian ethanol cost less than gasoline, the country is also a significant exporter of the fuel. Thus it is possible that initial subsidies can lead to viable nonsubsidized programs, and this is the hope of biomass fuel supporters in the United States.

Equitable distribution of biofuels and food resources

The fair and appropriate use and distribution of biofuel resources has several dimensions. First, how are the existing biofuels industries distributed geographically? Second, how might this pattern change when, and if, cellulosic biofuels are commercialized? Third, are there important indirect effects of the development of the biofuels industries on other crucial resources? In this section, each of these issues will be addressed in turn.

The existing biofuels industries (based on feedstocks, such as cornstarch, sugarcane molasses, rapeseed oil, soybean oil, and palm oils) are highly concentrated. As shown in Table 2 for the case of global ethanol production, just two countries—the United States and Brazil—account for a significant percentage of global output. In addition, the United States and China accounted for 40% and 6% of world corn production in 2006, respectively, yet China produced only around 20% of the ethanol output of the United States.[68,69] Brazil, in contrast, produced 6% of the world corn output in 2006 but relies on sugarcane feedstock to manufacture ethanol, as does

Table 2. **Top ethanol-producing nations (in millions of liters per year)**

Nation	2008
U.S.	34,069
Brazil	24,500
China	1,900
France	1,000
Canada	890
Germany	568
Thailand	348
Spain	317

Adapted from Renewable Fuels Association.[69]

India (although the latter also uses some cassava). Brazil and India are the world's two largest sugarcane producers, accounting for 58% and 23% of global output in 2005, yet the ratio of ethanol production in India to Brazil in 2006 was only 11%.[69,70] A similar geographic concentration exists for biodiesel production, with Europe accounting for around 75% of the total output (Table 3). However, these patterns may reflect the distribution of manufactured capital, choice of feedstock, overall transportation fuel consumption, and government policies more than geographic distribution of resources.

As the cellulosic biofuels industry is being developed, it is important to reflect on the geographic distribution of residues and wastes that can be used as feedstocks. These are quite diverse and hold promise to make the manufacture of this fuel (intellectual property issues aside) widely available around the world. Potential feedstocks include, but are not limited to, woody parts and residues from the processing of trees, plants, agricultural crops, grasses, and municipal solid and liquid wastes. While certain plant species may be most desirable or efficient, such as hybrid poplar, willow, switchgrass, miscanthus, jatropha, pongam, etc.,[14,24,38] such potential feedstocks are so widespread that the biofuel resources are readily available throughout most of the world. The few exceptions may be desert regions (e.g., Saharan Africa, Saudi Arabia), or countries with extremely high population densities (e.g., Bangladesh, Singapore, Taiwan).

Major concerns have been raised in the last 5 years regarding a potential conflict between food and fuel, and the impact on food access and food prices for the poor,[10] although it has also been noted that biofuels do not necessarily adversely affect food security since they can be produced on lower quality lands.[9] Until such time that a cellulosic biofuels industry is fully established, however, producers must rely on conventional food feedstocks. There are several dimensions to this issue. First, the major biofuel feedstock that is most likely to raise this problem today is corn. Second, the major corn-based biofuel producer, the United States, splits its corn crop among several major markets, i.e., animal feed (48%), human food (10%), ethanol (23%), and exports (19%) (data are for 2007[69]). Thus, the largest market for U.S. corn is by far animal feed. As the ethanol output has been growing the other markets have shrunk in percentage terms, although the corn output for direct domestic human consumption has remained small. However, from 2002 to 2008, a time of very rapid growth of the ethanol industry, the overall corn crop expanded by almost 40%. In addition, the growth of the corn-based ethanol industry has led to a commensurate increase in the output of the co-product animal feed, DDGS.

What these factors mean for the food versus fuel debate is that while the increasing demand for corn-based ethanol has undoubtedly had an adverse impact on both domestic and export corn prices and supply due to the cross-price elasticity of demand, especially in developing countries, a few recent studies and macroeconomic analyses may have exaggerated these effects.[9,15,73,74] The reason for this is the other major factor influencing the corn market is

Table 3. **Top 10 biodiesel-producing nations (in thousands of tonnes per year)**

Nation	2008
Germany	2,819
U.S.	2,203
Malaysia	1,972
France	1,815
Italy	595
Belgium	277
Poland	275
Portugal	268
Austria	213
Spain	207

Adapted from European Biodiesel Board[71] and National Biodiesel Board.[72]

oil prices, a critical component in the manufacture and shipping of food, and given the rapid rise and fluctuation in oil prices in the last few years price volatility may be more detrimental to food security for the poor.[14] Some analysts have examined these issues more broadly, such as through scenarios of increasing carbon prices and the impact on food prices, land prices, and the competitive effects on food and bioenergy crop production.[40,75,76]

Socio-economic issues

Related to the issues of biofuels, food security, and food prices, an expanded biofuels sector raises sustainable development challenges for rural economies. Since almost all the feedstock is located in rural areas, with the exception of municipal solid wastes, the influence of biomass energy programs on rural development is promising. Many such areas, especially small farms, welcome nonagricultural income, such as from energy resource development. Existing biofuels industries have been a major boon to rural economies and small farmers in several countries.[77–79] Since expanded biofuels development does not guarantee benefits to small-scale producers, certification systems could help.[80] In addition, liquid biofuels, such as vegetable oils and biodiesel, offer development opportunities for small- and medium-sized electric grids at the community and village level.[14]

Three major socio-economic issues associated with expanded biofuels development can be identified: small-scale financing, economic development and employment generation, and health and gender implications.[14] It can be expected that advanced biofuels technologies, such as cellulosic ethanol, especially small-scale, will have difficulty obtaining financing in some regions and countries because of high capital requirements and perceived high risk given the emergent nature of the market.[61] However, the upfront cost barrier can be overcome by utilizing low- or no-cost residues for feedstock, low-cost debt financing, and integration into a biorefinery platform.[81] Moreover, such projects would seem to be tailor-made for funding from the Global Environment Facility and the Energy Efficiency 21 Project of the United Nations Economic Commission for Europe.

The economic development and employment generation of an expanded biofuels sector will depend on the scale of industrial activity and regional concentration, as well as oil prices. For example, Solomon has shown that while second-generation biofuels technology is not very labor intensive, cellulosic ethanol refineries could result in a variety of modest, positive regional economic effects, especially during the plant construction period.[82] The analysis applied the Policy Insight model of REMI, Inc., a linked regional input–output (IO), econometric and economic base system, in the upper Midwest region of the United States. Most of the refinery jobs are likely to be highly skilled, requiring expertise in chemistry, engineering, and management. According to Solomon, even with inter-regional financial leakages, local economic effects could be relatively significant and positive in many rural agricultural areas.[82] Neuwahl *et al.* also used an IO framework to explore the job impacts of biofuels development in the context of the Renewable Energy Roadmap for the European Union market.[83] The authors found minor, although generally positive, net employment effects (losses in the services, energy, and transportation sectors due to economic inefficiency of the policy is compensated by gains in the agricultural, food, and industrial sectors). Finally, Sparovek *et al.* discussed how an expansion in sugarcane-based ethanol production in the Brazilian case could be integrated with native farmers and livestock ranchers.[84] In particular, a socio-economic expansion model was applied to the Pontal region, which found that regional income levels for the beef cattle and milk production sectors grew dramatically under the sugarcane integration scenario.

The health and gender implications of biofuels arise from the role that women play as the primary caretaker in homes. Since wood, charcoal, dung, and crop residues have been traditional sources of home cooking and heating fuel for millions of poor families worldwide, this has led to high levels of indoor particle and hydrocarbon inhalation, respiratory diseases, such as pneumonia, cancer, and even death.[85] These problems are especially pronounced among the poor in Southeast Asia and Sub-Saharan Africa,[14] where girls and women often walk long distances to collect biomass, and carry heavy loads home. Consequently, the substitution of advanced biomass-derived cooking fuels for traditional fuels in these regions could have significant health benefits, especially for women.[86,87]

Environmental emissions and effects

Given the predominance of gasoline and diesel fuels in transportation, most analyses of biofuels compare their emissions and environmental effects to the continued reliance on the former. Robertson *et al.* summarized recent literature on the most important environmental issues.[88] Most studies have focused on environmental problems caused or exacerbated by grain-based cropping systems—especially corn-based—which include potential carbon debt,[11] greater soil erosion, nitrate and phosphorus nutrient losses, decreased ground and surface water quality, mixed effects on air quality, large water demand, and biodiversity loss. Most of these problems can be decreased by better agricultural practices and technologies, e.g., the use of no-till farming, advanced fertilizers, riparian plantings, and water conservation.[88]

The life-cycle net greenhouse gas emissions from biofuels of carbon dioxide (CO_2), methane, and nitrous oxide are an important consideration. The consensus is that compared to the greenhouse gas emissions from conventional fuels, emissions from corn-based ethanol, biodiesel, and sugarcane or cellulosic ethanol are lower by 10–20%, 40–50%, and 85–95%, respectively.[46–48,52,55] The major exceptions have included Patzek[89] and Pimentel and Patzek,[45] who calculated higher greenhouse gas emissions, and Tilman *et al.*,[90] who calculated a CO_2 emissions reduction of greater than 100% with native grassland perennials. As noted by Larson, the major uncertain factors that have determined these varying results have included assumptions on prior land use, crop yields, nitrous oxide emissions, and co-product energy content.[91]

Air quality effects of using low biofuel blends are mostly positive. For example, ethanol and biodiesel blends reduce carbon monoxide emissions by 25–50%.[55,92] Biodiesel blends can reduce particulate emissions by almost half, and hydrocarbons by about two-thirds.[92] Ethanol blends, in contrast, usually raise emission levels of volatile organic compounds, though these can be reduced by lowering gasoline's Reid vapor pressure. Finally, nitrogen-oxide emissions are higher for both types of biofuel production and use, especially because of on-farm emissions from fertilizer usage.[45,55] Moreover, all of these conventional air emissions are higher with an 85% ethanol blend (E85) compared to gasoline per unit of energy released upon combustion.[93]

The water pollution and soil erosion resulting from the production of conventional biofuels are much more serious and more decidedly negative, especially for corn-based ethanol. These effects, however, can be avoided by switching to cellulosic feedstocks based on perennial crops and their residues grown on native and marginal lands, if the residue maintenance requirements for soils are strictly observed.[9,88,90] The negative effects include water pollution from runoff of significant farm inputs of chemical herbicides, insecticides and fertilizers, soil irrigation and salinization, erosion and reduced fertility of soils, wastewater generation, and biological oxygen demand.[39,94,95]

Large-scale biofuel production could lead to substantial demands for fresh water, both for cropping systems and for process water needs in biofuel refineries. These demands have been scarcely addressed. Exceptions have included Giampietro *et al.*,[31] Berndes *et al.*,[1] and Berndes.[96,97] The latter study found that the long-term water requirements for biofuels conversion are likely to be less than the evapotranspiration losses in energy crop production, and are generally less of a concern than the water pollution with the exception of already water-stressed countries. The latter finding was further explored by de Fraiture *et al.*,[98] who applied WATERSIM, a simulation model of water demands with and without biofuels development, to China and India for 2030. These authors concluded that the water demands in these countries would be highly significant. This underscores the need to shift to less water-intensive cropping systems and feedstocks, including agricultural and forestry residues, and move away from corn and sugarcane.[97]

The last, although not least, environmental effect of interest from large-scale biofuels production is on biodiversity. Most of the research in this area has focused on forest and grassland species, and is reviewed and critiqued by Flaspohler *et al.*[99] The authors discuss the known and potential biodiversity effects of biomass energy systems on both terrestrial and aquatic ecosystems. The growth of monocultures versus diverse feedstock species, feedstock productivity, competing land use, and water requirements receive special attention, as does the sustainability of bioenergy systems. Their review shows that to conserve biodiversity as well as soils, and to achieve greater ecosystem resiliency, biofuels systems should focus on lowering cultivation inputs and use native forest species or perennial plants in polycultures.[99,100] A related issue is that precautions should be taken, such as ecological studies of fitness responses to various environmental scenarios, so that non-native biofuel feedstocks do not become invasive plant species.[101]

Sustainable biofuels criteria

Given the major environmental concerns raised by large-scale biofuels development (food versus fuel, deforestation, water pollution, water scarcity, etc.), as well as the socio-economic considerations, over the last decade there has been a growing recognition of the need for development of sustainability criteria and certification standards for biofuels production and trade. Lewandowski and Faaij reviewed existing environmental certification systems for their applicability to the growing bioenergy trade.[80] A large range of social, economic, ecological, and other criteria were considered. This study made several findings and recommendations, including: there was a lack of "hard" and quantitative indicators in the existing certification systems; stakeholder involvement is required and should be represented in an international panel; available certification systems should be used with care; regional bioenergy certification and indicator case studies should be performed; a large range of specific and quantitative indicators needs to be developed; and both strict and loose criteria and indicator sets should be developed, and their impact on bioenergy production costs studied.

Two other recent papers are noteworthy on this subject. In one paper, Luzadis *et al.* developed a novel approach to assess bioenergy sustainability.[102] Their proposal took a systems approach, incorporating the latest scientific knowledge and social values. A five-step participatory approach that uses Norgaard's[103] co-evolutionary development process was outlined and applied with a bioenergy example in the Netherlands. The application showed how a participatory and more comprehensive approach to assessing sustainability could improve its validity, reliability, and efficiency over current approaches. In the second paper, Groom *et al.* made 12 timely policy recommendations to support biofuels certification standards.[100] These proposals can be summarized by three general principles: promote sustainable and low-impact feedstocks with a small ecological footprint, maintain native and essential food crop habitats, and require net carbon neutral biofuels.

Practical efforts to create biofuels sustainability criteria started to come to fruition in 2008. The first certification system for verified sustainable ethanol was created by the Swedish ethanol company SEKAB, and international principles and criteria have been proposed by the Roundtable on Sustainable Biofuels (based in Lausanne, Switzerland). In additional, the International Organization for Standardization is in the process of developing an international standard for solid biofuels (ISO/TC 238). The Swedish agreement is with the Brazilian ethanol company LDC Bioenergia, and requires that sugarcane be grown on farms applying zero tolerance to child and slave labor, and that the ethanol reduce CO_2 emissions by at least 85% compared to gasoline.[104]

The Roundtable on Sustainable Biofuels released "Version Zero" of its proposed principles and criteria in 2008. Following stakeholder feedback, a revised Version 0.5 was released in August 2009 (Table 4). Additional guidance and criteria have been provided for each of the principles. The Roundtable developed its draft based in part based on the work and experience of numerous sustainable agriculture and forestry initiatives, and has included stakeholder representation from around the world, meetings in South America, Asia, and Africa, and feedback through its Bioenergy Wiki.

The United States has also proposed limited biofuels standards as part of the Energy Independence and Security Act of 2007 (EISA). The RFS established by EISA for the first time will regulate CO_2 emissions in the United States, by requiring that all biofuels produced from new facilities (those not operating or under construction in December 2007) reduce greenhouse gas emissions by 20–60% over their life cycle. This will account for the direct and indirect emissions associated with growing, producing, distributing, and using these fuels. The EPA is required to issue regulations to implement these requirements.

Conclusions and prospects

Clearly there are many ways to examine the sustainability of biofuels beyond the resource supply and renewability of the feedstock. A variety of analyses

Table 4. Principles for sustainable biofuels, version 0.5

Principle	Explanation
1. Legality	Biofuel production shall follow all applicable laws and regulations.
2. Planning, monitoring, and continuous improvement	Sustainable biofuel operations shall be planned, implemented, and continuously improved through an open, transparent, and consultative Environmental and Social Impact Assessment (ESIA) and an economic viability analysis.
3. Greenhouse gas emissions	Biofuels shall contribute to climate change mitigation by significantly reducing life-cycle greenhouse gas emissions as compared to fossil fuels.
4. Human and labor rights	Biofuel production shall not violate human rights or labor rights, and shall promote decent work and the well-being of workers.
5. Rural and social development	In regions of poverty, biofuel production shall contribute to the social and economic development of local, rural, and indigenous peoples and communities.
6. Local food security	Biofuel production shall ensure the right to adequate food and improve food security in food insecure regions.
7. Conservation	Biofuel production shall avoid negative impacts on biodiversity, ecosystems, and High Conservation Value areas.
8. Soil	Biofuel production shall implement practices that seek to maintain soil health and reverse degradation.
9. Water	Biofuel production shall maintain or enhance the quality and quantity of surface and ground water resources, and respect prior formal or customary water rights.
10. Air	Air pollution from biofuel production shall be minimized along the supply chain.
11. Use of technology, inputs, and management of waste	The use of technologies in biofuel production shall seek to maximize production efficiency and social and environmental performance, and minimize the risk of damages to the environment and people.
12. Land rights	Biofuel production shall respect land rights and land use rights.

Adapted from Roundtable on Sustainable Biofuels.[105]

have shown that, unequivocally, corn-based ethanol is unsustainable and has significant environmental costs. The case for sugarcane-based ethanol and biodiesel based on a variety of feedstocks is less clear-cut, since these fuels also raise significant environmental challenges in some regions. Among the currently and foreseeable commercial biofuels, only cellulosic ethanol has the potential to be produced and consumed on a sustainable basis, based on all possible socio-economic and environmental criteria, including the meeting of soil residue maintenance requirements. There are many reasons for this conclusion: a larger resource and land base for the feedstocks, higher energy return on investment, potentially greater economically efficiency, equitable resource distribution, little or no conflict with food resources, and much lower greenhouse gas emissions and other environmental effects.

Despite the apparent advantages of cellulosic ethanol, such fuels will not be produced on a significant scale for another decade or so as they are slowly being commercialized around the world. Consequently, in the short term the environmental and socio-economic problems raised by conventional biofuels deserve serious attention. Especially important are concerns about food security and distribution, greenhouse gas emissions, soil erosion, water pollution, and water supply in arid or water-stressed regions. While most of these problems can be addressed through better farming practices (many of which require more fuel inputs), pressure to expand biofuels production makes these issues challenging.

The future development of biofuels thus seems bright, but it will be important to develop and apply biofuels sustainability criteria as soon as possible and in a consistent way worldwide. This will require increased cooperation among a large range of stakeholders and governments who support sustainable development, and who share a common concern for tackling the global climate change and petroleum challenges facing the world in the 21st century. The Roundtable on Sustainable Biofuels shows great promise for meeting this challenge based on the recent release of its draft principles.

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Conflicts of interest

The author declares no conflict of interest.

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