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Review

Biofuels, biodiversity, and people: Understanding the conflicts and finding opportunities

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ABSTRACT

The finitude of fossil fuels, concerns for energy security and the need to respond to climate change have led to growing worldwide interests in biofuels. Biofuels are viewed by many policy makers as a key to reducing reliance on foreign oil, lowering emissions of greenhouse gases and meeting rural development goals. However, political and public support for biofuels has recently been undermined due to environmental and food security concerns, and by reports questioning the rationale that biofuels substantially reduce carbon emissions. We discuss the promise of biofuels as a renewable energy source; critically evaluate the environmental and societal costs of biofuel use; and highlight on-going developments in biofuel feedstock selection and production technologies. We highlight net positive greenhouse gases emissions, threats to forests and biodiversity, food price increases, and competition for water resources as the key negative impacts of biofuel use. We also show that some of these environmental and societal costs may be ameliorated or reversed with the development and use of next generation biofuel feedstocks (e.g., waste biomass) and production technologies (e.g., pyrolysis). We conclude that certain types of biofuels do represent potential sources of alternative energy, but their use needs to be tempered with a comprehensive assessment of their environmental impacts. Together with increased energy conservation, efficiencies and technologies such as solar-power and wind turbines, biofuels should be included in a diverse portfolio of renewable energy sources to reduce our dependence on the planet's finite supply of fossil fuels and to insure a sustainable future.

Contents

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1. Introduction

Fossil fuels (oil, natural gas, and coal) contribute to ~80% of total world energy supply (Goldemberg and Johansson, 2004; Goldemberg, 2007). Depending on production and consumption rates, the presently known reserves of fossil fuels are estimated to last anywhere from 41 to ~700 years (Goldemberg and Johansson, 2004; Goldemberg, 2007). The finitude of fossil fuels, concerns for energy security and the need to respond to climate change have led to growing worldwide interests in renewable energy sources such as biofuels. An increasing number of developed [e.g., the United States (US)] and rapidly developing nations (e.g., China) see biofuels as a key to reducing reliance on foreign oil, lowering emissions of greenhouse gases (GHG), mainly carbon dioxide (CO_2) and methane (CH_4), and meeting rural development goals (Fulton et al., 2004; Armbruster and Coyle, 2006; Pickett et al., 2008). Between 1980 and 2005, worldwide production of biofuels increased by an order of magnitude – from 4.4 to 50.1 billion litres (bbl Fig. 1; Murray, 2005; Armbruster and Coyle, 2006), with further dramatic increases since (FO Licht 2008). However, political and public support for biofuels has been undermined due to environmental and food security concerns as well as by recent reports questioning the rationale that biofuels substantially reduce carbon emissions. The diversion of food crops or croplands to produce biofuels has been blamed for global food shortages and associated increasing costs of staple food crops such as maize and rice (James et al., 2008; Josserand, 2008; Rahman et al., 2008). Also, recent research suggests that certain biofuel production pathways may lead to net positive GHG emissions or substantial carbon debts (e.g., the conversion of carbon-rich peatland to oil palm plantations in Southeast Asia; Crutzen et al., 2008; Fargione et al., 2008; Scharlemann and Laurance, 2008; Searchinger et al., 2008). Nevertheless, some policy makers and scientists remain optimistic that with the development of 'next generation' biofuels such as cellulosic ethanol, there are real opportunities for using biomass to meet some of our energy needs (Farrell et al., 2006; Ragauskas et al., 2006; Field et al., 2008). The overall objectives of this review are to (i) discuss the promise of biofuels as a renewable energy source, (ii) critically evaluate the environmental and societal costs of biofuel use, and (iii) highlight on-going developments in biofuel feedstock (raw material) selection and production technologies, and the implications of these developments for biodiversity and conservation.

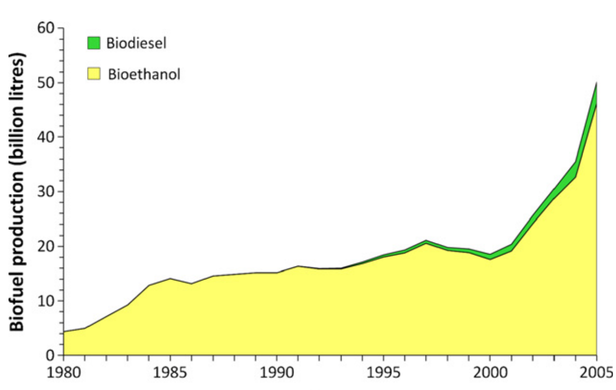

Fig. 1 – Increase in global production of bioethanol and biodiesel between 1980 and 2005. Data from Murray (2005) and Armbruster and Coyle (2006).

2. The promise of biofuels

Biofuels are renewable fuels derived from biological feedstocks, and include both liquid forms such as bioethanol (gasoline-equivalent) or biodiesel (diesel-equivalent), and gaseous forms such as biogas (e.g., methane) or hydrogen. In this review, we focus our discussion on liquid biofuels. Bioethanol is by far the most common biofuel in use worldwide (Fulton et al., 2004). Global bioethanol production increased from 4.4 bbl in 1980 to 46.2 bbl in 2005 (Fig. 1; Murray, 2005; Armbruster and Coyle, 2006; FO Licht 2008). The largest producers of bioethanol are the US (16.1 bbl in 2005), Brazil (16 bbl), and China (3.8 bbl). Bioethanol is produced from the fermentation of corn (*Zea mays*), sugarcane (*Saccharum* spp.), or other starch- or sugar-rich crops. Bioethanol can also be produced from cellulosic materials, including grasses (e.g., switchgrass [*Panicum virgatum*]), trees (e.g., willows [*Salix* spp.]), agricultural residues (e.g., wheat straws), or municipal solid wastes (e.g., paper) via more complex pathways (see Section 4.2). However, cellulosic ethanol is not yet commercially viable due to high production costs (Fulton et al., 2004).

Global biodiesel production increased from 11.4 million litres in 1991 to 3.9 bbl in 2005 (Fig. 1; Murray, 2005; Armbruster and Coyle, 2006). Germany, France, the US, and Italy are the leading producers of biodiesel (Fulton et al., 2004; Pahl, 2005; Koh, 2007). Biodiesel can be produced from vegetable oil (e.g., palm oil [*Elaeis guineensis*]), used frying oil, or animal fat through a transesterification process in which oil molecules (triglycerides) react with an alcohol (e.g., methanol) and a catalyst (e.g., potassium hydroxide) to form fatty acid-methyl esters (FAME or biodiesel) and glycerol (by-product). In Asia-Pacific, a number of biodiesel initiatives are being developed to capitalize on the region's immense palm oil production capacity. Indonesia – the world's largest producer of palm oil – recently announced plans to invest US$1.1 billion to develop eight to 11 additional palm oil-based biodiesel plants by 2010 (Armbruster and Coyle, 2006). The governments of Thailand, the Philippines, Singapore, Japan, Korea, China, and Australia are also actively pursuing energy policies aimed at increasing the production or use of biodiesel.

2.1. *Reduction of GHG emissions*

Between 1970 and 2004, global GHG emissions increased by 70% (Berstein et al., 2007). One proposed solution to rising atmospheric CO_2 levels is to 'decarbonize' energy production by substituting fossil fuels with biofuels (Pacala and Socolow, 2004). In its simplest analysis, biofuels are considered to be carbon neutral because all CO_2 released during biofuel combustion is offset by carbon fixation during plant growth. In reality, GHGs may be released during any phase of the biofuel production process – from feedstock agriculture, through biorefining, to biofuel delivery and final consumption. Therefore, the net benefit of biofuel use in terms of GHG balance can only be determined from a full lifecycle analysis (LCA). Studies over the past 15 years show that the displacement of gasoline or diesel by biofuels can result in average net reductions in GHG emissions of 31% for bioethanol, 54% for biodiesel, and 71% for cellulosic ethanol (Fig. 2; Supplementary Table S1). In the production of bioethanol, the use of sugarcane as a feedstock results in far greater GHG savings (92%) than any other bioethanol feedstock (Table S1). Also, the favorable numbers for cellulosic ethanol were derived from theoretical studies and laboratory experiments. The development of efficient and cost effective cellulosic ethanol production on commercial scales has immense but as yet unrealized potential that has attracted investments by private industry. While industrial production of cellulosic ethanol is not yet a reality, we believe that given recent developments and the potential benefits from commercialization, it will be a reality within the next decade. There is considerable variability in these estimates for each type of biofuel owing to different assumptions implicit in different studies. For example, the production of corn-based bioethanol also produces animal feed (corn meal) as a co-product, which could offset the production of equivalent items, such as soybean meal, and their associated GHG emissions. Studies that do not account for such 'co-product credits' typically reported net positive GHG emissions in biofuel use (e.g., Pimentel, 1991, 2001; Patzek, 2004; De Oliveira et al., 2005; Pimentel and Patzek, 2005). Another key factor influencing GHG balances is the type of process energy used during various stages of biofuel production. For example, powering farm tractors using natural gas releases less GHGs than doing so using diesel fuel (69 vs. 91 g CO_2-equivalent GHG per MJ; Wang, 2001). Furthermore, the production of sugarcane-based bioethanol in Brazil can be carbon neutral or even result in net carbon sequestration because almost all conversion process energy is supplied by the burning of 'bagasse' – fibrous remains of the crushed cane (Fulton et al., 2004). A crucial point is that none of the LCA studies reviewed in this section considered GHG emissions associated with land-use change (a topic we discuss in Section 3.1).

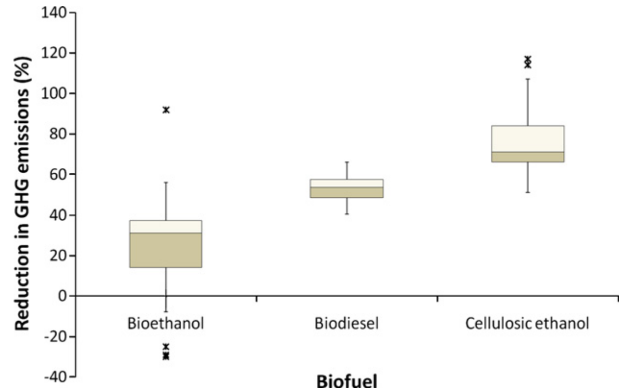

Fig. 2 – Estimates of net reduction in greenhouse gas (GHG) emissions from the displacement of gasoline or diesel use in transport by different types of biofuels, including bioethanol (corn-, wheat-, sugarbeet-, or sugarcane-based; number of data points, *n* = 22), biodiesel (rape- or soy-based; *n* = 10), and cellulosic ethanol (grass-, hay-, wood-, or crop residue-based; *n* = 13). In this box-and-whiskers plot the middle horizontal line represents the median, box hinges represent first and third quartiles, whiskers represent extreme values within 1.5 times the interquartile range, and asterisks represent outliers. Negative values reflect a net increase in GHG emissions. All calculations here ignore GHG emissions due to potential changes in land-use. See Table S1 for data sources and details.

2.2. *Energy security*

Analysts expect global oil consumption to continue to increase over the next 30 years – from 85 million barrels per day (mmb/d) in 2006 to 118 mmb/d in 2030 (Hester, 2006; EIA-DOE, 2007), and also predicted world oil production to peak between 2010 and 2020 (Kerr, 1998). The combination of insatiable global demand with expected production declines has obvious implications for energy security. Already seven of the world's 10 largest oil consumers are not producing enough oil to meet their domestic needs (Fig. 3; EIA-DOE, 2008a). Even Promethean optimists (Dryzek, 2005) who believe that technological advancements would ensure a longer lasting oil supply agree that the economic costs of extraction, and hence prices, are likely to increase (Penner, 1998, 2000; Ulgiati, 2001). Over the last few years, oil prices have indeed risen from ~US$25 per barrel in January 2000 to over US$140 per barrel in June 2008 (EIA-DOE, 2008a). Political instability in oil-rich regions, tighter oil supplies, and rising oil prices have prompted many countries to diversify their energy portfolio. Biofuels have gained popularity as they allow both a reduced dependency on oil imports and can be promoted as 'clean

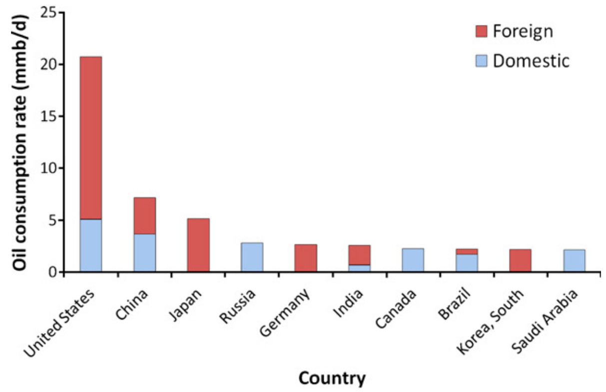

Fig. 3 – Consumption rates of the 10 largest consumers of oil (crude oil and petroleum products) in the world in 2006. Oil consumption rate is expressed as million barrels per day (mmb/d). The figure also provides a breakdown of oil sources: domestic = oil produced within the country itself; foreign = net oil import, which is calculated as total oil consumption – domestic oil production. Data from EIA-DOE (2008a).

energy' alternatives, thereby satisfying both energy security and environment (i.e., climate change) agendas.

Large-scale biofuel production was pioneered in Brazil where the biofuel industry was born of necessity – amidst the oil crises of the 1970s, when oil prices were high and sugar prices low (De Oliveira, 2002; Brazil Institute, 2007). To counter its dependence on foreign oil supplies, the (then military) government introduced mandatory ethanol-gasoline blending requirements and offered subsidies for the production of sugarcane-based bioethanol. It also spent billions of dollars to develop distilleries and distribution infrastructures, as well as to promote the production of E-100 fueled (pure ethanol-burning) vehicles. Since the late 1980s, Brazil has deregulated its biofuel sector (e.g., by eliminating direct subsidies) and pursued a less intrusive approach based on two key policy measures – a 20% blending requirement, and tax incentives favoring the use of bioethanol and flex-fuel vehicles (FFV; Brazil Institute, 2007). FFVs are a key element of bioethanol's success in Brazil because these vehicles can run on any blend of gasoline and bioethanol, giving the driver great flexibility at the pump (Hester, 2006). Today, over 80% of all vehicles sold in Brazil are FFVs that are served by ~33,000 gas stations offering both gasoline and bioethanol. Through the development of its bioethanol industry, Brazil was able to reduce its oil import bill by an estimated US$33 billion between 1976 and 1996 (Fulton et al., 2004; Sims et al., 2006). More importantly, the use of bioethanol, which now accounts for 40% of Brazil's transport fuel market, helped the country achieve self sufficiency in oil consumption (Hester, 2006).

2.3. *Rural development*

The recent biofuel-led increases in food prices should come as no surprise to some proponents of biofuels. In fact, those who see biofuel use as benefiting rural development would be counting on food prices to rise. Even before concerns of a food crisis surfaced in mid-2007 (James et al., 2008; Josserand, 2008; Rahman et al., 2008), several simulation modeling studies had projected that greater biofuel demand and production would lead to higher world prices not only for biofuel feedstocks but also for other food or feed crops that compete for the same agricultural land (Raneses et al., 1998; Walsh et al., 2002; Koizumi, 2003; Fulton, 2004; Westcott, 2007), although it should be noted that other factors also contribute to high food prices (see Section 3.3). Analysts anticipate that higher prices of food and feed commodities would spur the agricultural sector to respond by increasing production (De La Torre Ugarte, 2006). This would translate to higher employment rates and wages for the rural poor (farmers), particularly in many developing countries where agricultural activities are labor-intensive. There is some evidence to support this: small-scale farmers in Jambi, Sumatra, for example, are investing in oil palm (for edible oil or biodiesel) and rubber (in response to increasing demand for natural rubber due to high price for oil from which synthetic rubber is derived) (P. Levang, personal communications; and J.G., personal observations). Furthermore, greater investments into agriculture could help improve yield and production efficiencies (De La Torre Ugarte, 2006; Rosegrant et al., 2006; Pickett et al., 2008). In this way, the rural poor could become major beneficiaries of greater biofuel use both directly and indirectly. However, most analysts acknowledge that landless poor consumers in both rural and urban areas may ultimately suffer as a result of higher food prices (see Section 3.2).

3. Environmental and societal tradeoffs

Despite the considerable benefits of biofuel use, they are not without their tradeoffs. We discuss some of these below.

3.1. *Net GHG emissions from land-use change*

Increasing biofuel production capacities will likely lead to substantial land-use change directly and indirectly (Koh, 2007; Righelato and Spracklen, 2007). Direct land-use change occurs when non-agricultural lands, or diverse agroforestry systems, are converted to grow biofuel crops. Conversion may be undertaken on a large scale by biofuel companies often encouraged by government policy, on a medium scale by entrepreneurs who negotiate land-use rights to forest and a share of the profits with local communities, or on a much smaller scale by individual farmers opportunistically encroaching on forest land (Casson, 1999). Conversion of diverse agroforests often involves individual decisions by farmers, but can also be instigated by agreement negotiated between companies and communities who lend their land to companies for conversion to, for example, oil palm, in return for a share of the profits (as is widespread in Jambi, Sumatra; P. Levang, personal communications). Indirect land-use change occurs when the diversion of current food or feed crops (e.g., corn), or croplands (e.g., corn fields) to produce biofuels (e.g., corn-based bioethanol) causes farmers to respond by clearing non-agricultural lands to replace the displaced crops. Such land-use change may in turn contribute to GHG emissions through upfront costs incurred from the loss of carbon stored in above- and below-ground biomass when land is cleared; and/or opportunity costs from the loss of the carbon sequestration service of converted land-uses (e.g., growing forests).

Recently, Searchinger et al. (2008) evaluated that increasing corn-based bioethanol production in the US by ~75% (56 bbl) by 2016 would require a diversion of 12.8 million ha of existing cropland in the country to corn production for bioethanol consumption. The resultant declines in US agricultural exports (e.g., wheat by 31%) could drive agricultural expansion worldwide – by an estimated 10.8 million ha, including 2.8 million ha in Brazil, 2.2 million ha in the US, 1.2 million ha in India, and 1.1 million ha in China (Searchinger et al., 2008). These indirect land-use changes would in turn result in the release of 3.8 billion mega-tons of CO_2-equivalent GHGs – a biofuel carbon debt that would take 167 years for corn-based bioethanol use to repay (Searchinger et al., 2008). However, one has to keep in perspective that the area displaced by the planting of biofuel crops is a relatively small proportion of the 1.5 billion ha of arable and permanent cropland worldwide (FAO, 2008). In a separate analysis, Fargione et al. (2008) calculated biofuel carbon debts for six different scenarios of directly converting native habitats to grow biofuel crops: Malaysian or Indonesian lowland tropical rainforest to oil palm; Malaysian or Indonesian peatland to oil palm; Brazilian Amazon to soybean; Brazilian Cerrado to soybean; Brazilian Cerrado to sugarcane; and US central grassland to corn. Their analysis reveals that these land-use changes would result in carbon debts of between 33 and 3003 tons of CO_2 per ha, which would require between 17 and 423 years to repay.

3.2. *Threats to tropical forests and biodiversity*

Besides contributing to GHG emissions, biofuel-driven agricultural expansions can also lead to land-use conflicts among different stakeholders. Recently, Koh (2007) investigated the potential habitat and biodiversity losses that may result from an increase in global biodiesel production capacity to meet future biodiesel demands (an estimated 277 million tons per year by 2050). Koh estimated substantial increases in cultivated area for all major biodiesel feedstocks, including soybean in the US (33.3–45.3 million ha), sunflower seed in Russia (25.7–28.1 million ha), rapeseed in China (10.6–14.3 million ha), and oil palm in Malaysia (0.1–1.8 million ha) (Fig. 4). Furthermore, because soybean and oil palm are most intensively cultivated in biodiversity hotspots (soybean: Atlantic forest and Cerrado in Brazil; oil palm: Sundaland, Wallacea, and Guinean Forests of West Africa; Mittermeier et al., 2004; FAO, 2008), any future intensification of soybean or oil palm production, without proper mitigation guidelines, will likely further threaten the high concentrations of globally endemic species in these areas.

Indeed, environmentalists have become increasingly concerned about the impacts of rapidly expanding feedstock agriculture in the tropics. For example, several non-governmental organizations (NGO) have accused oil palm growers in Southeast Asia of destroying large tracts of tropical forests and threatening the survival of many native species, including the orang-utan (*Pongo pygmaeus*) (Koh and Wilcove, 2007). In response, oil palm producers have accused NGOs of unfairly targeting the oil palm industry in Southeast Asia while ignoring biofuel feedstock agriculture in other regions, such as soybean cultivation in South America. Producers also argue that oil palm cultivation is not a threat to biodiversity because only disturbed forests or pre-existing croplands have been converted to oil palm with minimal disturbance to pristine habitats. Based on land-cover data compiled by the Food and Agriculture Organization of the United Nations, Koh and Wilcove (2008) estimated that between 1990 and 2005, 55–59% of oil palm expansion in Malaysia, and at least 56% of that in Indonesia occurred at the expense of forests. Furthermore, the authors reported that the conversion of either primary or secondary (logged) forests to oil palm would result in significant biodiversity losses (Koh and Wilcove, 2008). Similarly, the conversion of diverse agroforestry systems within forested landscape mosaics to oil palm-dominated stands represent further losses of diversity and the isolation of remnant patches of forested habitats (e.g., across many parts of Indonesia; Casson, 1999). Because palm oil is widely used both as food (e.g., for frying) and fuel (i.e., biodiesel), the spread of oil palm agriculture is a particularly worrisome threat to tropical biodiversity.

Demand for biofuels and the resulting impact on food prices may further indirectly affect forests and biodiversity by undermining new incentive-driven systems for environmental conservation. The opportunity costs of adopting payment for environmental service (PES) schemes such as reducing emissions from deforestation and degradation (REDD; http://carbonfinance.org/), may be substantially increased thereby reducing their attraction to land owners and managers, and to governments or companies who would be investing in such schemes. For example, a recent study estimated that at current palm oil prices (~US$1000 per ton crude palm oil), the option of converting a hectare of peatland

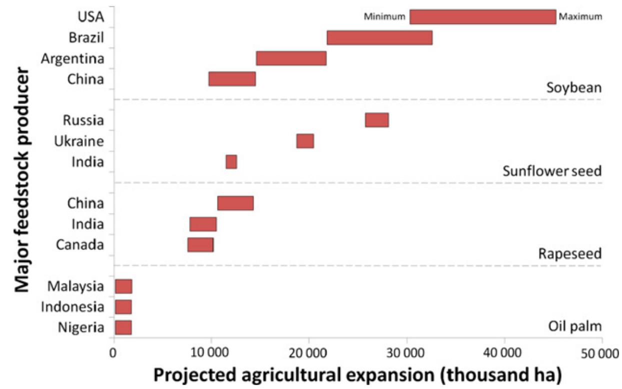

Fig. 4 – Projected agricultural expansion in major biodiesel feedstock producers for the scenarios of soybean-, sunflower seed-, rapeseed-, or oil palm-based biodiesel production to meet global biodiesel demand in 2050. Minimum estimates were made assuming that 50% of existing arable and permanent cropland in the country (agricultural land; *sensu* FAO 2008) will be converted to biodiesel feedstock before non-agricultural lands are converted. Maximum estimates were made assuming all expansion of feedstock agriculture will occur in non-agricultural lands. For more details, see Koh (2007).

for palm oil production would generate a cumulative net income (~US$10,300 over 25 years) comparable to the option of conserving the land for carbon offsets (US$2000–12,900, depending on carbon prices) (Fig. 5; Butler, 2007). These figures do not account for costs of transactions or conditionality assessments, both of which may be substantial for PES schemes. Additionally, the price of palm oil has more than doubled in the last two years (Fig. 5), and will likely remain high (World Bank, 2008), further relegating the profitability of PES.

3.3. *Impacts on food prices and the poor*

For decades before 2000, declining food prices have allowed millions of people worldwide to escape from poverty (James et al., 2008; Rahman et al., 2008). However, since the turn of this millennium, prices of basic food commodities, such as wheat and rice, have climbed steadily (Fig. 6; Josserand, 2008). In 2007 and 2008, price increases of staple foods reached alarming proportions (Fig. 6) – triggering concerns of a global food crisis that has been widely reported in the media (The Economist, 2008). During this period, export prices of wheat increased by 130%, rice by 98%, and corn by 38% (Rahman et al., 2008). Among the most gravely affected are the poor who spend 50–60% of their income on food (Von Braun, 2008). As many as 1.2 million Asians are at greater

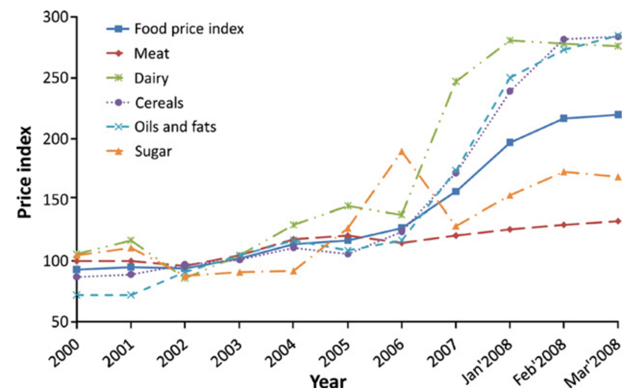

Fig. 6 – Food commodity price indices from 2000 to 2007, and the first three months of 2008. The Food and Agriculture Organization of the United Nations (Josserand 2008) calculated the meat price index based on meat product quotations of four meat groups, including poultry, bovine, pig, and ovine, weighted by world average export trade shares for 1998–2000; the dairy price index based on price quotations of butter, skim milk powder, whole milk powder, cheese, and casein weighted by world average export trade shares for 1998–2000; the cereals price index based on grains and rice price indices weighted by average trade share for 1998–2000; the oils and fats price index based on average of 11 different oils weighted with average export trade shares for 1998–2000; the sugar price index based on International Sugar Agreement prices; and the overall food price index based on the average of the above commodity group price indices weighted with average export shares of each group for 1998–2000.

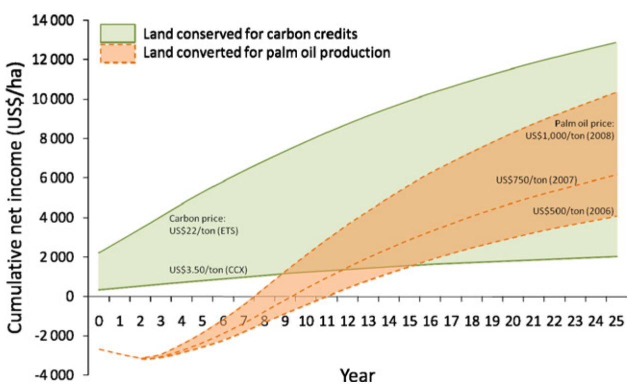

Fig. 5 – Comparing cumulative net income between the options of conserving peatlands for carbon offsets and converting them for palm oil production. Incomes are net present values (NPV), assuming a 15% discount rate and 10% interest rate. Carbon incomes were calculated assuming yields of 100 tons per ha for the first year and 27 tons per ha for subsequent years. Palm oil incomes were calculated assuming age-based variable yields (4.8 tons per ha on average), and at a 40% profit margin. Carbon prices are based on the European Union Emission Trading Scheme (ETS; http://ec.europa.eu/environment/climat/emission.htm) for the high estimate and the Chicago Climate Exchange (CCX; http://www.chicagoclimatex.com/) for the low estimate. Palm oil prices are the average price of crude palm oil traded in Malaysia in 2006, 2007, and May 2008 (http://econ.mpob.gov.my/economy/EID_web.htm). For more details, see Butler (2007).

risks of malnutrition and food deprivation because of the inflation in food prices (Rahman et al., 2008).

The underlying causes of rising food prices are many and complex. They include factors such as adverse weather conditions that affect crop productivity, speculative or precautionary demand for food commodities, and inappropriate policy responses such as export bans of foods (James et al., 2008; Josserand, 2008; Rahman et al., 2008). More important are structural factors that include rising energy costs, stagnation in crop productivity, policy inadequacies or failures that constrain agricultural development, climate change, rising demand for higher value and grain-intensive foods (e.g., meat), and diversion of crops or croplands to biofuel production. Among these factors, biofuels have borne the brunt of the blame due largely to the media's sensationalisation of the 'food vs. fuel' debate. A popular allegory to illustrate the impacts of biofuels on food equates the grain required to fill the tank of a sports utility vehicle to grain that could otherwise feed a person for an entire year (Byerlee et al., 2008). Although biofuels may have received a disproportionate amount of the blame for increased food prices, it clearly does deserve some of the blame: the use of corn to produce bioethanol in the US has increased from 6% of total corn production to 23% over the last three years (Rahman et al., 2008), and this has undoubtedly contributed to tightening food supplies and rising food prices.

3.4. *Competition for water resources*

Set against the backdrop of the energy and food crises is yet another unfolding and arguably more insidious threat to human survival and well-being – that of a water crisis. Pressures on water supply are increasing worldwide due to population growth, rural-to-urban and transboundary migrations, global climate change, natural disasters, poverty, and warfare (WWAP–UNESCO, 2006). Additionally, agricultural expansion in response to higher prices for food commodities will likely further add to the demand for irrigation. In many developing countries, the lack of clean water and sanitation often results in malnutrition, diseases, and deaths. Agricultural expansion for biofuels may compete with other uses for water and thus contribute to rising water demands (Pickett et al., 2008). The extent to which biofuel use will exacerbate the water crisis depends on how much irrigation is required to grow biofuel crops, which will vary with the type and location of the crop being cultivated. In the US, irrigation accounts for the majority of the nation's consumptive use of water (i.e., water that does not become available for reuse). Biofuel production in the US could have significant regional and local impacts where water sources are already stressed (Schnoor et al., 2008). For example, the displacement of soybean by corn (to produce corn-based bioethanol) will result in greater water usage in the Northern and Southern Plains. In other regions of the world, such as Malaysia or Indonesia, abundant rainfall supplies much of the water needed for agriculture. In these regions, drainage is a greater concern for farmers than irrigation, and the production of biofuel crops (e.g., oil palms for biodiesel) is not expected to have a dramatic impact on water availability (Corley and Tinker, 2003). However, feedstock agriculture is not the only process in biofuel production that requires water. Pate et al. (2007) and Phillips et al. (2007) estimated that biorefineries consume 4 gallons of process water per gallon of bioethanol produced (gal/gal), largely from evaporative losses during the distillation of ethanol following fermentation. This means that a biorefinery producing 100 million gallons of bioethanol per year would use the equivalent of the annual water supply for a town of 5000 people. In comparison, water use in petroleum refining is about 1.5 gal/gal (Pate et al., 2007).

4. The future of biofuels

Over the last few years, biofuels have garnered worldwide interests for their potential to reduce GHG emissions, improve energy security, and enhance rural development. At the same time, reports on the environmental and societal costs associated with biofuel production have stirred up a storm of controversy. Nevertheless, there remain several silver linings – in terms of on-going developments in feedstock selection and production technologies – that may yet allow biofuels to fulfill their promise as a viable source of renewable energy.

4.1. *Next generation feedstocks*

Almost all of the commercially available biofuels today are produced from either starch- or sugar-rich crops (for bioethanol), or oilseeds (for biodiesel). As discussed above, producing biofuels from these sources is less than ideal because they compete with food or feed production. Recent research attention has turned to the use of dedicated feedstocks for biofuel production, including perennial grasses, wood, macroalgae, and agricultural, forestry, or municipal wastes. The candidate grass species for cellulosic ethanol production include switchgrass, miscanthus (*Miscanthus* spp.), reed canary (*Phalaris arundinacea*), and giant reed (*Arundo donax*) (Lewandowski et al., 2003). Most of these crops can be cultivated on marginal or agriculturally degraded lands, and thus may not compete with food production. High-diversity mixtures of grassland species can even provide greater bioenergy yields and GHG reductions than certain conventional bioethanol or biodiesel production systems (Tilman et al., 2006).

Forest plantations and agroforestry systems can also serve as potential sources of cellulosic feedstocks for bioethanol production. Over the past four decades, new forest plantations in the United Kingdom (UK) have been increasing at an average rate of 25,000 ha per year – mostly in Scotland, northern England, and Wales (Milne and Cannell, 2005). The planted species in these forests include Sitka spruce (*Picea sitchensis*), Scots pine (*Pinus sylvestris*), lodgepole pine (*Pinus contorta*), hybrid larch (*Larix* spp.), Douglas fir (*Pseudotsuga* spp.), and noble fir (*Abies procera*). Although these forests have been planted for timber, they could also be harvested to supply biofuel production. Nevertheless, inappropriate planting on peat soils, which are widespread in the upland regions of the UK and particularly Scotland, could release more carbon than is sequestered in the long term (Cannell et al., 1993; Malhi et al., 1999).

Macroalgae is another potential source of biofuel feedstock. Aquatic unicellular green algae, such as *Chlorella* spp., are typically considered for biodiesel production owing to their high growth rate, population density, and oil content (Campbell, 2008). Algae have much higher productivity (90,000 l of biodiesel per hectare [l/ha]) than soybean (450 l/ha), rapeseed (1200 l/ha), or oil palm (6000 l/ha; Haag, 2007). In addition to their high yields, macroalgae cultures are not land-intensive and may provide further benefits of wastewater remediation or nutrient reduction (Schneider, 2006; Campbell, 2008).

Waste biomass forms a diverse group of potential feedstocks which include agricultural (e.g., wheat straw), forestry (e.g., wood pieces leftover after timber extraction), and municipal wastes (e.g., waste paper, waste food scrapes, used cooking oils). A recent study estimated that a city of one million people could provide enough organic waste (1300 tons per day) to produce 430,000 l of bioethanol a day, which could meet the needs of about 58,000 Americans, 360,000 French, or 2.6 million Chinese at current rates of per capita fuel use (Worldwatch Institute, 2006). Horticultural waste biomass (e.g., tree trunks, twigs, and leaves) could also be a potential source of cellulosic feedstock (Koh et al., 2008). The authors estimated that the 50,000–156,000 tons of horticultural biomass collected each year from about 1 million planted trees in Singapore can be used to produce 14–58 million litres of bioethanol that can displace 1.6–6.5% of the country's transport gasoline demand.

4.2. Next generation technologies

In addition to diversifying the biofuel feedstock resource base, there is also a need to develop process technologies that convert these next generation feedstocks to liquid fuels. The two primary pathways for converting biomass to biofuel are biochemical and thermo-chemical conversion. Biochemical conversion pathways are used to convert cellulosic biomass to biofuel by breaking down the recalcitrant components of plant material – cellulose (40–60%) and hemicellulose (20–40%) – into sugars, which are then fermented to produce ethanol (Fulton et al., 2004; Hamelinck et al., 2005; Worldwatch Institute, 2006). The limiting factor in terms of yield is the rate of cellulose breakdown, which can be accomplished by either acid or enzymatic hydrolysis. Acid hydrolysis involves the use of either dilute acid at high temperatures, which is cheap but low yielding, or concentrated acid at low temperatures, which is high yielding but expensive. Biochemical research has also focused on the use of enzymes (cellulases) produced by bacteria or fungi (e.g., *Trichoderma reesei*) to hydrolyze cellulose (Hamelinck et al., 2005). Many experts believe that enzymatic hydrolysis is the key to cost-effective bioethanol production in the long term. A second limiting factor in biochemical conversion pathways is the inability of yeasts used in conventional industrial applications (e.g., beer fermentation) to digest five-carbon sugars (e.g., xylose) produced from the breakdown of hemicellulose. Xylose-digesting yeasts were discovered in the 1980s (Hamelinck et al., 2005), and a major focus of current research is to search for new strains of microorganisms, including bacteria, yeasts, and fungi that can perform this function efficiently.

Thermo-chemical pathways for converting biomass to biofuel include gasification and pyrolysis (Bridgwater, 2003; Fulton et al., 2004; Worldwatch Institute, 2006). Cellulosic biomass can be gasified in a high-temperature (600–1100 °C) vessel at low oxygen levels to produce 'syngas' – a mixture of carbon monoxide, carbon dioxide, hydrogen, and methane (Worldwatch Institute, 2006). Syngas can then be converted to a variety of fuels, including hydrogen, methanol, or dimethyl ether (DME). Synthetic diesel and gasoline can also be produced from syngas by Fischer–Tropsch (FT) synthesis. A major advantage of the gasification/FT pathway is that all organic matter in biomass (including lignin) can be converted to liquid fuel, which makes it a more efficient conversion process than biochemical methods. Because the gasification of fossil fuel feedstocks (e.g., coal) is a well established technology, there is potential for adapting existing infrastructure for gasification (i.e., 117 plants worldwide) to produce bioethanol from biomass feedstocks (Worldwatch Institute, 2006). Pyrolysis is the thermal decomposition of biomass in the absence of oxygen to produce liquid 'bio-oil', solid 'bio-char' (charcoal), and light gases (Bridgwater, 2003; Worldwatch Institute, 2006). Fast/flash pyrolysis, in which biomass is heated to 500 °C for less than ten seconds, is used to maximize bio-oil production. Several undesirable characteristics of bio-oil (e.g., does not mix well with petroleum products) make it more suitable as a fuel in boilers or stationary engines to generate heat or electricity than as a transportation fuel. Bio-char is a by-product of pyrolysis and can be added to soil as a stable carbon store (helps sequester CO_2) and to retain soil nutrients (improving soil fertility and reducing pollution from water run-off; Lehmann, 2007). Germany, France, and Sweden are the main drivers of research into thermo-chemical conversion technologies. The key challenge is to improve the cost effectiveness of thermo-chemical processes, including gasification and pyrolysis, as well as downstream processing of syngas and bio-oil into biofuel end-products (Worldwatch Institute, 2006).

Biotechnology may also determine the future role of biofuels (Fulton et al., 2004; Kintisch, 2008). Advances in plant genomics could lead to the production of higher yielding biofuel crops, reducing both land requirement and energy input, which may reduce land-use conflicts and GHG emissions (Fulton et al., 2004), although lower production costs may also enable greater penetration of the transportation fuel market, which may in turn increase biofuel demand and the amount of agricultural land required to grow biofuel crops (Feng and Babcock, 2008; Keeney and Hertel, 2008). Biofuel crops may also be genetically engineered to be more resistant to pests, diseases, or abiotic stresses (e.g., drought), which would insure a stable supply of feedstock (Vinocur and Altman, 2005; Ragauskas et al., 2006). Furthermore, dedicated biofuel crops may be genetically modified to grow faster, have lower lignin content, or even contain cellulases within the crop biomass itself in order to enhance the efficiency of cellulosic ethanol production (Sticklen, 2006).

4.3. Implications for biodiversity and conservation

New developments in biomass conversion pathways and biotechnology have considerable potential to maximize the delivery of energy from biofuel crops as well as waste plant material, leading to increases in yield, reductions in pesticide and fertilizer requirements, and greater resistance to drought. Furthermore, efficient biomass energy extraction methods coupled with greater agricultural productivity can reduce the land area requirement for biofuels and alleviate pressure on both natural habitats and land for food production. Of course, many of the social concerns relating to genetically engineered crops and industrial plant production still apply (e.g., health risks), but insofar as current concerns relating to biofuels centre around the clearance of forested land or displacement of food cropping areas, biochemical energy extraction from genetically modified crops appears to be a potential solution. Furthermore, the public may be more amenable to genetic modification of dedicated energy crops, such as switchgrass, because they are not consumed by humans (Fulton et al., 2004).

On the other land, the development of more efficient biomass conversion pathways may make it economically feasible to harvest large swathes of savannah grassland or provide additional economic incentives to clear natural forest lands. If this happens, biofuel production will continue to pose a threat to biodiversity. This underscores the importance of continual research and development on policies concerning biofuel production, use and trade. In particular, policy instruments to enhance the traceability of biofuel feedstocks

Table 1 – Estimated current and future costs of different biofuels compared with that of petroleum fuels retailed in the United States in May 2008

Fuel	Price (US cents/litre)	
	Current	2030
Retail gasoline	91	–
Retail diesel	105	–
Bioethanol from sugar cane	25–50	25–35
Bioethanol from corn	60–80	35–55
Bioethanol from beet	60–80	40–60
Bioethanol from wheat	70–95	45–65
Bioethanol from cellulosic biomass	80–110	25–65
Biodiesel from animal fats	40–55	40–50
Biodiesel from vegetable oils	70–100	40–75
Fischer–Tropsch synthetic fuels	90–11	70–85

All fuel prices are exclusive of taxes (11% for gasoline and diesel). Data for biofuels were taken from Table 6.1 in Pickett et al. (2008). Data for gasoline (all grades) and diesel (on-highway; all types) fuels were from EIA-DOE (2008b).

need to be developed to ensure that they are produced in environmentally and socially responsible ways.

5. Conclusion

Rising fuel prices coupled with concerns about carbon emissions are making biofuel production more cost competitive and attractive (Table 1). There are global implications for the shift towards biofuels, and in this review paper, we have highlighted net positive GHG emissions, threats to forests and biodiversity, food price increases, and competition for water resources as the key negative impacts of biofuel use. On the other hand, we have also shown that the development and use of next generation biofuel feedstocks and production technologies may reduce some of the environmental and societal costs associated with biofuels. We conclude that certain types of biofuels do represent potential sources of alternative energy, but their use needs to be tempered with a comprehensive assessment of their environmental impacts. In recent years, there has been a policy driven and economically facilitated drive for biofuel production, and only now are the environmental costs of this becoming apparent. A careful evaluation of potential costs and benefits of the range of biofuel production processes is needed to shape more informed policy in the future. Nevertheless, we believe that together with increased energy conservation, efficiencies and technologies such as solar-, wind-, geothermal-, and hydroelectric-power, biofuels should be included in a diverse portfolio of renewable energy sources in order to reduce our dependence on the planet's finite supply of fossil fuels and to insure a sustainable future for our species.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.biocon.2008.08.005.

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