

Introduction: Biofuels and the Environment in the 21st Century

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Biofuels are combustible materials derived directly or indirectly from biomass (plants or organic wastes). Their use in industrial countries is being promoted as a way to increase energy independence and security and a sustainable way to reduce greenhouse gas emissions while contributing to farmer income (BRDi 2008; FAO 2008b). In developing countries, biofuels are being used to promote development by opening a new business opportunities, creating jobs, and increasing incomes. Whether biofuels can deliver these benefits and at what cost has been questioned. Production of biofuels may result in a variety of environmental consequences brought by changes in land use, expansions in agriculture, changes in agricultural practices, transport-ation of the biomass used to make biofuels, conversion of the biomass into fuels, and disposal of the remaining waste materials after fuels are made.

Several studies over the past few years have highlighted environmental concerns (Hill et al.

2006; Keeney and Muller 2006; Tilman et al. 2006; WWI 2006; Bringezu et al. 2007; Crutzen et al. 2007; Martinelli and Filoso 2007; Donner and Kucharik 2008; Searchinger et al. 2008; Simpson et al. 2008; Keeney 2009), but for the most part, the analysis of the environmental consequences of biofuels is very recent, highly uncertain, and often controversial. Most recent analyses indicate a range of environmental concerns and benefits that vary greatly depending on several factors, including: (1) the biomass feedstocks and the cultivation methods used; (2) the type of biofuel; (3) the technology used to convert the biomass into fuel; (4) the type of energy used to power the conversion; (5) the location where the feedstocks and biofuels are produced; and (6) the extent to which a growing demand for biofuels induces changes in land use and land cover.

The Scientific Committee on Problems of the Environment (SCOPE) of the International Council of Science (ICSU) established the

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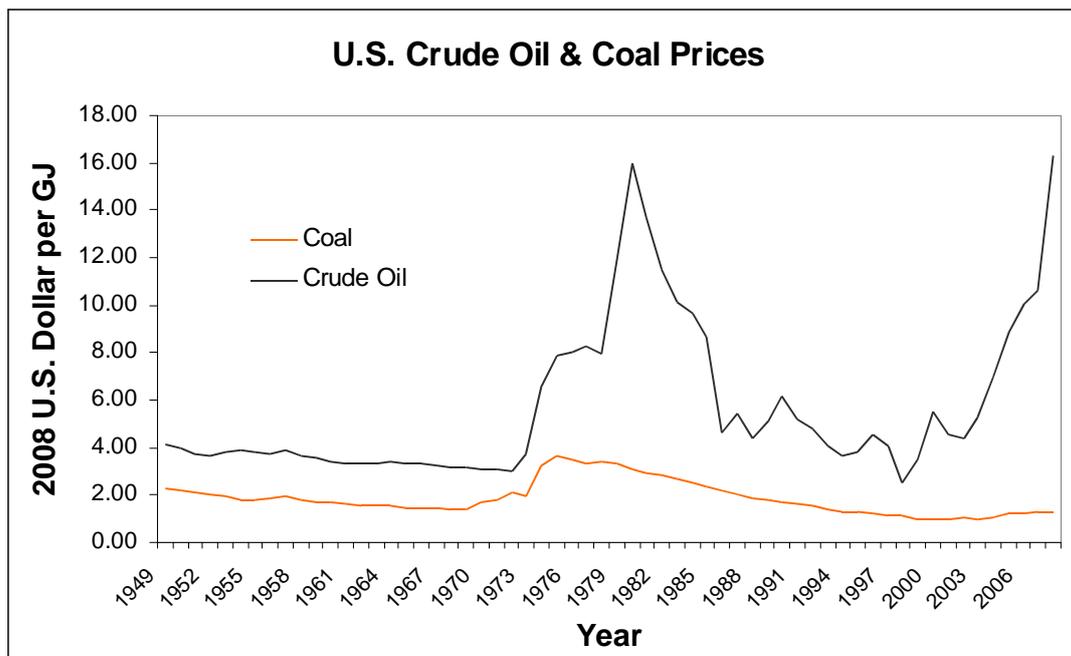
International SCOPE Biofuels Project to provide a comprehensive, objective, science-based analysis of the environmental benefits and problems of commonly used and potential future biofuels. The SCOPE International Biofuels Project held a workshop in Gummersbach, Germany from September 22-25, 2008 as a start towards this goal. This chapter introduces the proceedings from that workshop.

Often the term “biofuel” is used only to describe liquid biofuels, and “biomass energy” is used to describe solids such as wood. However, the term “fuel” generally includes solid materials such as coal, and the Merriam-Webster Dictionary defines a biofuel as “a fuel . . . composed of or produced from biological raw material,” specifically including wood (Biofuel 2009). Thus, biofuels include solid

fuels that are directly burned for heating and cooking (wood, dried dung), several liquid fuels, and methane gas made by fermentation or pyrolysis of biomass. Liquid biofuels include ethanol, other alcohols, and several oils (commonly referred to as biodiesel), including fatty acid methyl esters (FAME).

Biofuels are not new. The use of wood and charcoal as fuels is ancient, and liquid biofuels were critical in the development of early internal combustion engines and automobiles. The first internal combustion engine ran on ethanol, as did the first versions of the Model T Ford and Rudolph Diesel originally conceived his engines to run on peanut oil. However, fossil fuels dominated the energy picture of the 20th century, and biofuels have played a major role only in the poorest nations, and mostly as solid biofuels used for cooking and heating.

Figure 1.1 Price for coal and for crude oil in the United States, adjusted for inflation, in 2008 US dollars per gigajoule (or 10^9 joules), expressed free-on-board (FOB), or price at point of first sale, excluding freight or shipping and insurance costs. Data for crude (USD/bbl) from inflationdata.com (2008); data for coal (USD/ short ton) from EIA (2007, 2008). Conversion to USD per GJ calculated assuming energy values of 43.5 GJ per ton for crude oil and 27 GJ per ton for bituminous coal are assumed (http://bioenergy.ornl.gov/papers/misc/energy_conv.html)



Much of the recent interest has been in liquid biofuels, as these can readily replace conventional transportation fuels without major modifications in transportation networks. The dominance of liquid fuels as energy drivers for transportation systems is a consequence of the convenience and energy density of liquid hydrocarbons. The high demand for the convenience of liquid fuels has resulted in a large price differential between liquid and solid fossil fuels. For example, in the United States, the cost for oil has consistently been greater than for coal (per unit energy of fuel purchased) for more than 50 years, and the price differential has been steadily growing since 2000 (Figure 1.1). As of 2007 (the last year for which data were available when this chapter was written), oil cost 12 times more than coal for equivalent energy. This price differential, combined with the need to reduce carbon dioxide (CO₂) emissions and increase domestic energy security, has helped focus government biofuel policies on liquid fuels to replace oil, with little if any focus on solid biofuels. Most of the scientific analysis of the consequences of biofuels on the environment has also focused on liquid biofuels, and this was the dominant focus of the SCOPE Rapid Assessment work-shop in Gummiesbach and of the chapters in this book. Nonetheless, we suggest that solid biofuels may appropriately play a greater role in the future, for both economic and environmental reasons. It is important to note too that solid biofuels already supply approximately 10% to 13% of the global energy use, compared to just 0.4% from liquid biofuels in 2006 (FAO 2008b; REN21 2008).

Global Trends in Liquid Biofuel Production

The major liquid biofuels currently produced are ethanol and biodiesel, with ethanol production being far greater at the global scale

(Figure 1.2a). Global production of ethanol grew rapidly following the oil shortages of the 1970s from virtually nothing in 1975 to approximately 15 billion liters per year in 1985 (an energy equivalent of approximately 300 petajoules). The rate of increase then slowed, but production of ethanol increased over the next decade or so to approximately 20 billion liters per year in the late 1990s (an energy equivalent of approximately 400 petajoules). Global biodiesel production was negligible until the 21st century, but production has been increasing exponentially since 2000. Despite this increase, however, production of biodiesel is dwarfed by that of ethanol: in 2006, biodiesel made up 23% of the energy content of produced ethanol (Figure 1.2a).

The global production of liquid biofuels is dominated by just a handful of countries. The combined production of ethanol in Brazil and in the USA has accounted for 75% or more of the global production for decades (Figure 1.2b). China and India are the next largest producers, together accounting for 12% of global ethanol production in 2006 (RFA 2009). Almost 80% of the world's production of biodiesel occurs in the European Union, and almost 50% in Germany as of 2006 (REN21 2008).

Despite the exponential increase in the production of liquid biofuels since 2000, these fuels are very small contributors to the global energy picture. In the context of total energy consumption, liquid biofuels supplied only 0.4% in 2006 (IEA 2008; OECD/FAO 2008; REN21 2008). In terms of liquid fuels used for transportation, biofuels contributed 1.8% globally, with fossil fuels making up 98.2% of global use (OECD/FAO 2008). Liquid fuels are also used for heating and industrial uses, and globally 60% of liquid fuels are used in transportation (IEA 2008). Therefore, as of 2006, biofuels made up just over 1% of total liquid fuel use globally (Jank 2008).

Ethanol production

Brazil was the early leader in the production of ethanol creating its Proalcool Program 2 years after the 1973 global oil crisis. The goal of the plan was to produce ethanol from sugarcane to reduce oil imports and avoid dependence on imported oil (Goldemberg et al. 2008). From 1975 to 1986, ethanol production increased from 600 million to 12.3 billion liters per year (Figure 1.3a) and Brazil contributed more than 80% of the global production through the mid 1990s (Figure 1.2b).

As of the mid 1980s, the number of cars produced in Brazil that could run on pure hydrated ethanol was larger than that of traditional gasoline-fueled cars (Figure 1.3b). In the early 1990's, most Brazilian sugarcane was used to produce sugar for human consumption, and not ethanol, due to the combination of low oil and high sugar prices on the international market. Consequently, ethanol fuel lost credibility with consumers, and the production of cars fueled by pure ethanol decreased sharply from 1990 to 1995 and practically stopped by the beginning of 2000. Ethanol production remained constant, but as anhydrous ethanol that can be blended with gasoline (20% to 26% ethanol) in a mixture called gasohol for use as fuel in conventional combustion engines (Figure 1.3a). From 1995 to 2000, ethanol production increased significantly, largely due to the production of anhydrous ethanol for gasoline blends. This increase has continued since 2000 because the search for a renewable fuel to replace fossil fuel has been aided by the production of flex-fuel cars, capable of running on both hydrated ethanol and anhydrous blends. Flex-fuel cars now form almost 50% of the Brazilian fleet (Figure 1.3b). The year 1999 marked an important benchmark: the Brazilian government ended price controls and subsidies

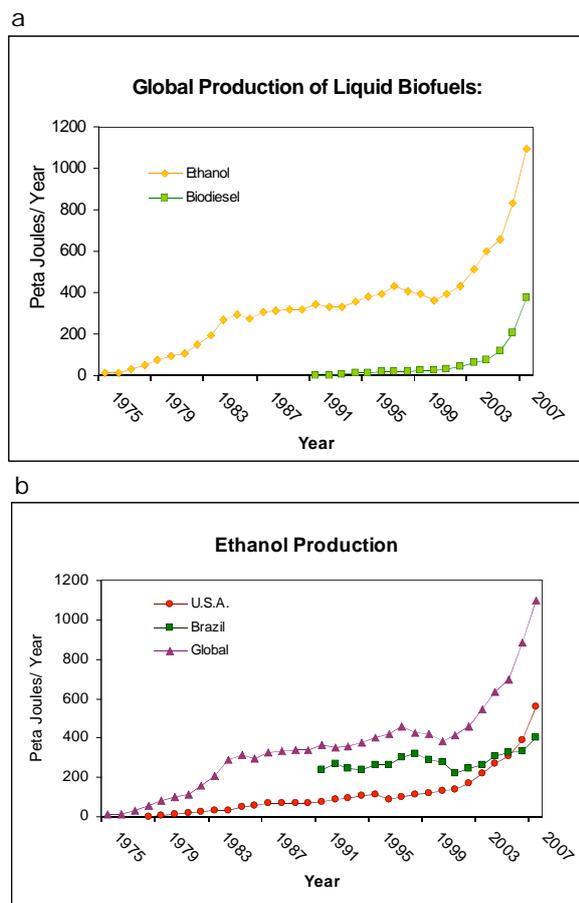
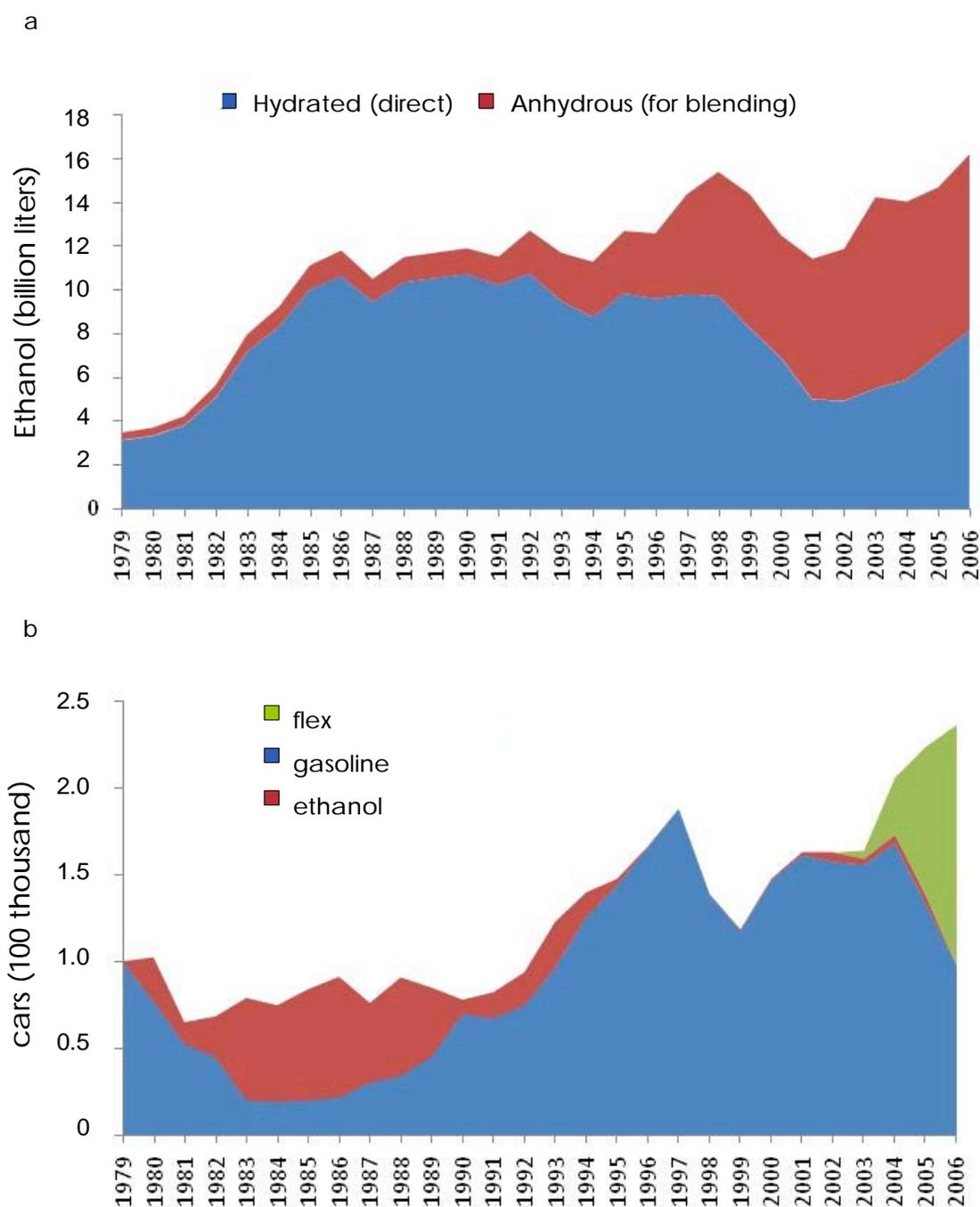


Figure 1.2 Global production of ethanol and biodiesel (1.2a) and comparison of production of ethanol in the USA and Brazil with global production (1.2b) from 1975 to 2007. A petajoule is 10^{15} (one quadrillion) joules. Energy contents of ethanol and biodiesel are estimated as 21 and 34 megajoules (10^6) per liter, respectively (http://bioenergy.ornl.gov/papers/misc/energy_conv.html). Data from Brown 2008; FAO 2008; UNICA 2008

to producers and production costs for ethanol decreased significantly (Goldemberg et al. 2004). As of 2007, ethanol contributed 15% of the liquid fuel use for Brazil, with fossil fuels supplying the rest (EPE 2008).

The United States is the other major producer of ethanol in the world (Figure 1.2b), with production growing steadily through the 1980s and 1990s. Several federal policies drove this

Figure 1.3 Trends in the production of hydrated and anhydrous ethanol in Brazil (1.3a) and trends in the production of cars in Brazil that burn ethanol, gasoline, or both (1.3b) from 1979 to 2006. Data from ANFAVEA (2008).



increase, including tax exemptions and subsidies for domestically produced ethanol that varied between \$0.12 to \$0.15 USD per liter (\$0.40 to \$0.54 USD per gallon) and equally large tariffs on importation of ethanol (Tyner 2008). Since 2000, ethanol production in the United States has accelerated exponentially, matching Brazil's production by 2005 and driving the exponential increase in global ethanol production (Figure 1.2a). Until 2005, there were no significant changes in federal policies to support the growing domestic ethanol production (Tyner 2008). Thus, the rapid increase in the 21st Century is driven largely by the concurrent increase in crude oil prices acting in concert with the long-existing tax incentives, subsidies, and tariffs. The 2005 Energy Policy Act set renewable fuel standards for ethanol production of 14 billion liters (290 petajoules) by 2006 and 26 billion liters (580 petajoules) by 2012. Actual production in 2006 greatly exceeded this target, and the 2012 target was met in 2007 (Figure 1.2b; Tyner 2008).

With the Energy Independence and Security Act of 2007, the United States set a goal of producing 54 billion liters of ethanol (1,130 petajoules) from corn by 2022. The country is rapidly moving towards that target, with an estimated 35 billion liters (730 petajoules) produced in 2008 (based on extrapolation of production rates for the first 10 months of 2008; RFA 2009). As of the fall of 2008, enough new ethanol plants were under construction to increase the capacity in the United States to a level of 51 billion liters (1,060 petajoules) per year, if all these plants are finished (Keeney 2009). Many experts expect that corn ethanol production in the United States is likely to peak at only a slightly greater value – 57 billion liters per year (1,200 petajoules) – due to economic pressures on corn prices that would make higher production unprofitable (Tyner 2008, and references cited therein). Already in 2007, the United States was using 24% of the total

national corn harvest to produce ethanol (FAO 2008a; National Agricultural Statistics Service 2008). The resulting ethanol supplied 1.3% of the nation's liquid fuel use (EIA 2008).

The Energy Independence and Security Act of 2007 also set a renewable fuel standard for “advanced biofuels” of 70 billion liters per year by 2022; much of this is expected to be ethanol production from cellulose (Tyner 2008) and would correspond to 1,500 petajoules per year. Advanced biofuels and cellulosic ethanol are discussed further below.

Ethanol production is expected to continue to grow globally over the next several years. Although Brazil and the United States will continue to dominate, other nations are expected to greatly increase production. One estimate predicts ethanol production in the European Union will be 12 billion liters per year (250 petajoules) and in other countries 15 billion liters per year (320 petajoules of energy) both by 2012 (Jank 2008). For comparison, ethanol production in Brazil is predicted to be 37 billion liters (780 petajoules) by 2012 (Jank 2008).

Biodiesel production

Germany was the leading country in biodiesel production in 2006 with 2.8 billion liters (175 petajoules), 48% of the world total. The other countries of the European Union accounted for another 30% of global biodiesel production, the U.S. for 15%, and minor quantities were produced in Brazil, China, India, Canada, Colombia, and Malaysia (REN 21 2008). Biodiesel production in Germany began in 1991 with a small pilot plant producing 11 thousand liters per year (ABI 2002). The rapid growth in production and use in Germany since then is attributable to strategic market development, driven by the UFOP agro-industry alliance with active participation by automobile industry

and policy-makers (ABI 2002; Runci 2005; van Thuijl and Deurwaarder 2006). By 1995, the nation's first commercial-scale biodiesel plant was on-line. The German auto industry was quick to respond with engine adaptations and warranties to guarantee the safe use of pure biodiesel. The phasing out of leaded gasoline in 1996 provided space in fueling stations across the country (van ABI 2002; Thuijl and Deurwaarder 2006), allowing pure biodiesel fuel to enter the public market. In 1999, the government introduced an ecotax (in addition to the existing mineral oil tax) for all fossil fuels including fossil/ biofuel blends. Pure biodiesel remained fully exempted and its market position strengthened.

In 2004, the German government, with approval from the European Commission, extended the tax exemption to biodiesel blends, leading to historically high investments in production capacity (van Thuijl and Deurwaarder 2006). By 2005, more than a million hectares had been planted with rapeseed, the dominant feedstock for German biodiesel, and production capacity had reached almost 2.2 billion liters, or 2 million tons (EEB 2008). By 2006, Germany had exceeded the EU non-binding 5.75% target for biofuel substitution with biofuels making up 6.5% of domestic transportation fuel demand. But, as crude oil prices rose, the price gap between fossil diesel and biodiesel came to exceed the limits outlined in the EU Energy Taxation Directive (2003/96/EG), and the European Commission declared Germany's tax exemption of biodiesel overcompensating. In 2006, the German energy law imposed taxes of 0.07 € per liter tax on all biodiesel and biodiesel blends for 2007 with annual increases which would bring the tax to 0.45 € per liter by 2012. Shortages in rapeseed feedstock added additional costs to production. On 1 January 2007, the German government introduced a legal minimum-blending quota of 4.4% (by

energy content) for all diesel fuel sold (as a sub-quota; total quota, including ethanol substitution set at 8% until 2015) in an effort to mobilize feedstocks and stabilize the market. Quantities in excess of the quota are eligible for tax reductions. The new framework ensured that all fuel sold in Germany would now contain biodiesel, substituting roughly 8.6% of total diesel fuel consumption. However, it also had some negative consequences: the demand for pure biodiesel collapsed and the high cost of domestic production opened the market to influxes of cheaper feedstocks and biodiesel blend imports, particularly from the United States. Imported fuels did not always meet German quality standards, causing engine problems and public dissatisfaction. Domestic production capacity increased until 2007, but then was reduced to less than 50%, raising concerns about an imminent collapse of the German biodiesel industry (EEB 2008). Germany nevertheless substituted 7.6% of its transport fuel demand with biofuels in 2007, with biodiesel accounting for 5.6%.

The EU has extended and revised its previous, non-binding target by setting a legal minimum of 10% renewable fuel share for all transportation fuel by 2020. Various fuels may contribute (including electricity) as long as they are based on renewable sources, and only alternative fuels that meet established GHG savings and limits on biodiversity impacts will count towards the legal quota, thus limiting imports of higher-impact biofuel blends. The German government has even more ambitious goals, though lower than the 17% target proposed at Meseberg in 2007, with the renewed biomass strategy in 2008 addressing a target range of 12-15% total energetic contribution to transport fuel consumption by 2020. To meet national and EU goals, both Germany and the EU must overcome current feedstock shortages induced by land limits and the high

cost of agricultural production. Recent studies have shown that German fuel producers are already using substantial shares of import-ed raw materials. For example, chemical analysis performed in 2008 revealed that about 20% of all biodiesel for blending was from imported soybean feedstocks (Greenpeace 2008a). Another study showed that biodiesel from palm oil was mixed with other agrodiesel or agrodiesel blend fuels at rates of 5-25% and sold in Germany (Greenpeace 2008b). This is consistent with ambitious plans to expand biodiesel production in countries such as Malaysia, Indonesia, Argentina and Brazil to supply global markets (REN21 2008).

Food vs. fuel

Currently, almost all ethanol is produced from sugarcane (mostly in Brazil) and corn (mostly in the United States). Most biodiesel comes from crops such as rapeseed (canola oil), soybean, and oil palms. As all these crops are also used for food, this clearly sets the stage for competition between food and biofuels for crop production, a competition that is already imposing major strains on regional and global food supplies (OECD/FAO 2007). As of 2007, only 5% of the global production of cereals (wheat, corn, rice, sorghum) was used to produce biofuels, with most used for direct human consumption or for animal feeds (FAO 2008a). However, the rate of increase in cereal use for biofuels is far greater than that for food use; FAO (2008a) estimates that of the 55 million ton increase in demand for cereals globally in 2007, only 25 million tons was attributable to food and feed. A greater actual increase in the tonnage of cereals used went to biofuels. In the United States alone, increased use of corn for ethanol production in 2007 was estimated to be 49 million tons, or an increase of 37% over the already rapidly increasing 2006 usage (FAO 2008a). As noted previously, 24%

of the US corn harvest was used to produce ethanol in 2007. Between 2006 and early 2008, corn prices rose from \$87 USD per ton to \$217 USD per ton, driven by increases in global food demand, use of corn for ethanol, crude oil prices, and trading policies and speculation across all commodities, as well as the relatively inelastic agricultural supply (Tyner 2008). Despite a 4.6% increase in global production of cereal crops in 2007, global stocks of cereals are at their lowest levels since 1982 and continue to fall (FAO 2008a). Use of cereals for biofuel production, and particularly the production of ethanol from corn in the United States, clearly contributes to this trend. (FAO 2008b).

As of 2006, Brazilian sugarcane covered an area of approximately 7 million hectares, with half of this area dedicated to the production of ethanol and half dedicated to the production of sugar. The expansion of sugarcane area in 2007 was approximately 10% of the total area or 0.7 million hectares (Conab 2008). Most of the expansion was on pastureland (65%), followed by 17% on soybean and 5% on corn and orange, respectively (Conab 2008). It seems that the loss of approximately 0.5 million hectares of pastures in Brazil is not affecting the meat production because the animal density in Brazil is still very low, around 1 head per hectare. Therefore, a small increase in animal density can compensate for losses of pastureland. Although still very controversial, so far it seems that the expansion of Brazilian sugarcane area is not pressuring food prices in the country (Goldemberg et al. 2008; Smeets et al. 2008). A major potential problem in Brazil is the displacement of soybean from Central Brazil by sugarcane towards the Amazon region, increasing the pressure for more deforestation in the region (Martinelli and Filoso 2008).

A recent report for the Renewable Fuels Agency of the United Kingdom emphasized the

desirability of moving biofuel production away from reliance on crops and croplands that could otherwise supply products for human consumption (Gallagher 2008). As biofuel production increases globally, the potential for competition between biofuels and food production will intensify. Even if non-food crops are used as the feedstock for the biofuels, the potential for competition with food production exists if the biofuel crops are grown on land capable of producing food (Searchinger et al. 2008). This issue is discussed in detail in Chapter 4 (Connor and Hernandez 2009). The interaction between food production and biofuels in the context of rural development in Africa and other underdeveloped regions is discussed in Chapter 15 (Bekunda et al. 2009).

Constraints with current liquid biofuels and potential futures for biofuels

Current generation biofuels exhibit a number of shortcomings that can present significant limitations in today's demanding markets. For one, after microbial fermentation, ethanol must be distilled to reduce its water content to acceptable levels; this is an inherently energy-costly process, particularly to produce the anhydrous ethanol that dominates production in the United States and is becoming increasingly important in Brazil. Ethanol is also both corrosive and hygroscopic, making it more difficult to store and transport than liquid fossil fuels, which can be distributed via pipelines. Rather, ethanol must be transported by trains, ships, barges, or trucks, increasing both economic and environmental costs. Furthermore, the combustion energy density of ethanol is more than one-third less than that of gasoline due to its 35% oxygen content. Hence an ethanol-powered vehicle incurs a one-third fuel-economy penalty. The high oxygen content is often viewed as positive when ethanol is used as a fuel additive for gasoline: in the

United States, the Clean Air Act of 1990 required oxygen additives in gasoline, and ethanol became the major additive in many states after MTBE was banned for health and environmental concerns. Ethanol as an additive to gasoline does reduce emissions of carbon monoxide (CO) and volatile organic compounds. Recent evidence, however, indicates ethanol blended with gasoline may actually increase some emissions of nitrogen oxides (NOx) (Pang et al. 2008). This is of concern, as increases in NOx are the major cause of ground-level ozone and smog and contribute to many problems associated with the global acceleration of the nitrogen cycle (Vitousek et al. 1997; Galloway et al. 2003).

Current biodiesel fuels are also not ideal. Fatty acid methyl esters (FAME) tend to have poor cold flow properties (e.g. some FAME types can freeze at ambient temperature), which may limit the amount of FAME that can be blended into diesel fuel, depending on ambient temperature. Biodiesel is often mixed with fossil fuels to make bio-petrodiesel blends, and most vehicle manufacturers suggest using blends only if they contain 10% or less biodiesel. However, blending is often not done accurately, and one recent study found that of 10 retail samples of diesel blends marketed in Massachusetts as 20% biodiesel, one was only 11% and another was 74% biodiesel (Reddy et al. 2008). Hydrogenated vegetable oil and "biomass-to-liquid" (or BtL) fuel are non-oxygenate blend components that allow higher blends, fully fungible in the diesel supply chain with better cold flow properties than FAME.

Many see "second-generation ethanol," or the production of ethanol from fermentation of cellulose, as a major part of the future of liquid biofuels. Cellulosic ethanol can be produced from crop stubble or stover (the stalk and leaves after harvesting grain), straw, trees, or

perennial grasses such as switchgrass. This may reduce or eliminate food-fuel competition, although growing switchgrass or trees such as willows or poplars on land that could otherwise be used for producing human food crops is still problematic. Competition between the energy and the material uses of biomass products is also an issue. For instance, in Germany use of wood pellets for heating increasingly competes with traditional biomass-based industries (e.g. plywood and pulp and paper production), which are also supplied by forest and saw mill byproducts (Bringezu et al. 2008). Ethanol's physical properties (corrosiveness, low energy density, etc.) are also, of course, still a limitation for cellulosic ethanol. In addition, removing crop stubble from the field may adversely affect the carbon balance of the soil, which could affect crop production as well as carbon sequestration (Ismail et al. 1994; Andrews 2008; Lal 2008). The issues associated with using corn stubbles for ethanol production are discussed in detail in Chapter 4 (Connor and Hernandez 2009).

Currently, the cost of producing ethanol from cellulose is estimated at \$102 per barrel of crude oil equivalent (\$17 USD per GJ; Dept. of Energy estimates, as cited in Tyner 2008). The price of oil has fluctuated greatly in recent decades, but almost always has been below this critical threshold (Figure 1.1). During the summer of 2008, oil prices were briefly in the range of \$150 USD per barrel (\$25 USD per GJ), but as of the writing of final revisions to this manuscript in January 2009, prices were back down to less than \$50 USD per barrel (\$8.20 USD per GJ). Clearly, cellulosic ethanol is not competitive with current technologies in such a market. A great deal of research is focused on reducing the cost of producing cellulosic ethanol, and the US Department of Energy has set a target production cost of \$47 per barrel of crude oil equivalent (\$7.70 USD per GJ; Tyner 2008).

Moving to pure hydrocarbon biofuels such as BtL potentially improves energy content, removes oxygen, increases fossil-energy efficiency, and reduces well-to-wheel emissions of CO₂. Next-generation biomass synthetic fuels are under development using a variety of catalytic processes (e.g. gasification and Fischer-Tropsch synthesis, enzymatic conversion of sugar to hydrocarbon, hydro-treating of vegetable oil). Some experimental synthetic fuels are demonstrating energy density and octane/cetane ratings substantially in excess of conventional fuel, using advanced processes. Moving to non-oxygenated biofuels also overcomes many of the issues of corrosion and cold-flow inherent in oxygenated biofuels. In these next-generation bio-hydrocarbon fuels, performance properties can be engineer-ed to improve energy and power delivery, thereby improving overall transport efficiency and emissions. Furthermore bio-hydrocarbon fuels can be used in conventional engines in greater concentration than current biofuels (Gallager 2008). As with any fuel dependant on land-intensive crops, however, issues of land-use competition still apply.

Other promising alternatives to ethanol are gaseous fuels such as methane (often called "biogas") and hydrogen. These can be produced from waste materials such as animal manure, from cellulose feedstocks such as wood and grasses, and from traditional crops such as corn. Per mass of corn, production of biogas results in 3-times greater or more useful energy than does the production of ethanol (SRU 2007). In part, this is because the biogas is not soluble in water and readily separates itself, whereas the distillation of ethanol from water requires a substantial input of energy. Note that biogas and hydrogen can be used as transportation fuels. Biogas can be directly burned in internal combustion engines designed to burn gasoline, with only slight modification, and both biogas and hydrogen

can be used with fuel cells to power electric vehicles.

The fundamental yield and cost of biofuel production may be significantly impacted by developments in agricultural practice and the feedstocks used for energy. Already the high yield of Brazilian sugarcane helps to underpin more cost effective and carbon-efficient production in this region. Production of biodiesel from equatorial palm oil is demonstrating some cost and carbon benefits that are attractive to governments, producers and exporters. Plants such as switchgrass and miscanthus offer the potential for rapid growth and high-energy yield. Marine algae offer the potential for even higher energy yield from lipids that would be cultivated using sea water in areas not currently used for agricultural production; however, suitable sites may be limited in area, and the economic costs and environmental consequences remain virtually unstudied. Many companies and institutions are exploring the application of genetic modification to increase energy yield and make plants more able to thrive in less environments where current crop production is low.

New crop species may also contribute to higher degrees of energy production in the future. For example, jatropha is a hardy oilseed plant with a reputed capacity to grow on “degraded” and “marginal” lands, actually improving soils and reversing erosion (Chiavari 2008). Jatropha is now promoted in India and Africa, with the former targeting 11 million hectares by 2012 (Das & Priess 2008). Reported yields in India range between 1 to 2.8 tons ha⁻¹ seed harvest without irrigation and 5 to 12 tons ha⁻¹ with irrigation (AEA 2008). The oil content of seeds is around 30% (Van Eijck & Romijn 2006), and Jongschaap et al. (2007) reported extractable oil yields of 540 to 2,700 kg ha⁻¹ yr⁻¹ (with 1.5 to 7.8 t dry seed ha⁻¹ yr⁻¹ and 35% seed oil content). At the same time, however, they

warned that high yield projections from degraded land, where Jatropha must be planted if it is to avoid food-fuel competition, should be regarded critically, as there is a lack of quantitative productivity data from trials under sub-optimal conditions (Jongschaap et al. 2008). Note that “degraded” lands include both those that have lost fertility from excessive use and those that are marginal due to environment (Connor and Hernandez 2009). Other potential problems include the plant’s toxicity, seeds which rapidly degrade, the hygroscopic nature and high viscosity of the produced oil, and little available information on biodiversity impacts and greenhouse gas emissions (van Eijck & Romijn 2006; AEA 2008).

Net energy return

The biomass used to produce biofuels is inherently a less dense and lower quality energy source than that of the crude oil used throughout most of the 20th Century. The fertilizer and machinery used in growing the crops consumes energy. Transporting the crops to a processing plant takes energy, often a lot of energy because the crops are a heavy, diffuse source of energy. Converting the crop feed-stocks to liquid forms requires energy, and in the case of ethanol, distilling the fuel from water takes further energy. Also, in the case of ethanol, transporting the fuel to point-of-use can be energetically more expensive than transporting liquid fossil fuels, as existing fuel pipelines cannot be used with ethanol.

Pimentel et al. (1988) were perhaps the first to emphasize that the gross energy available from burning a biofuel can be substantially different from the net energy available from the fuel after accounting for energy inputs from fossil fuels need to produce it. In the case of producing ethanol from corn, Pimentel et al. (1988) as well as Pimentel in a series of later papers (see Patzek 2004) argued that more

energy went into producing the fuel than was returned when the fuel was used. That is, the net energy balance ratio (energy output divided by energy input) can be less than one. These estimates remain controversial (Farrell et al. 2006), and most recent estimates indicate an energy balance for corn-ethanol that is greater than one (Hill et al. 2006; Field et al. 2007). This change from a net energy sink to a net energy source from the corn-ethanol system may reflect better data and more accurate methods for estimation compared to the early work of Pimentel et al. (1988), or it may reflect improvements in the efficiencies of growing corn and producing ethanol. In any event, even the more recent estimates for energy balance show a rather meager return: to obtain 1.25 joules of energy from ethanol produced from corn requires on average an investment of 1 joule of fossil fuel energy input (Hill et al. 2006). Ethanol from sugarcane has a much more favorable energy balance, in terms of return on inputs of fossil fuel energy (Goldembert et al. 2008; Macedo et al. 2008). For each ton of sugarcane, the fossil fuel energy input is equivalent to 210 MJ and the energy output close to 2,190 MJ, yielding an energy output ratio around 9 (Macedo et al. 2008). Other biofuels also show a more favorable net energy balance than does the corn-ethanol system (Table 1.1). Even these more favorable balances are far lower than that for producing gasoline or diesel from crude oil, though, where the net energy balances have historically ranged from 20 and higher (Cleveland et al 1984). The balance for energy from crude oil is declining since the time of “peak oil” has passed (currently ranging from 10:1 to 15:1), and increasingly greater amounts of energy must be used to find and extract the crude from remaining reservoirs.

The net energy ratios shown in Table 1.1 and virtually all of the published work on net energy ratios for biofuels are based on energy

Table 1.1 Net energy potential from crude oil and from biofuel crops using current technologies and future cellulosic technologies. The net energy balance ratio is defined as the output of usable energy divided by the input of fossil-fuel energy needed to produce the energy. Adapted from Field et al. (2007); net energy balance for crude oil is from Cleveland et al. (1984).

Feedstock Type	Net Energy Balance Ratio (output/ input)
Corn kernel	1.25
Sugar cane	8
Cellulosic biomass	5-4
Soy oil	1.9
Palm oil	9
Rapeseed oil	2.5
Crude oil	10-15

inputs from fossil fuels. One of the reasons that ethanol production from sugarcane in Brazil shows a relatively favorable energy ratio is that fossil fuel inputs are low, and the energy costs for processes such as the distillation of the ethanol are met almost entirely by burning the organic waste material left over after crushing the stalks (i.e. bagasse). We suggest that in the future, the total energy inputs used to produce biofuels – including energy from organic wastes such as bagasse – be considered in evaluating alternative fuels and technologies. Otherwise, opportunity costs for other energetic uses of the organic wastes cannot be fully considered. For example, if the bagasse were not used to distill ethanol, it could instead be used to generate electricity.

Interestingly, in considering the total energy supply for Brazil in 2007, bagasse provided more energy overall (13.6% of total national energy use) than did ethanol (4.3% of total national energy use; EPE 2008). Since many if not most of the environmental problems from biofuels come from land use and land conversion to grow biofuel crops, minimizing land use should be an important goal. This suggests directing as much as possible of the total available energy from the biofuel crop (including for example bagasse) into energy of direct use to society rather than into processing the biofuel. That is, biofuel technologies that minimize processing energy are preferable (all other considerations being equal), even when the processing energy comes from waste streams.

Emission of greenhouse gases

The net energy balance is an important consideration with regard to determining the net greenhouse gas emissions from use of a biofuel. The lower the ratio of net energy balance, the more fossil fuels that are combusted to obtain the energy of the biofuel, and therefore the less favorable are the net greenhouse gas emissions. There is not a one-for-one mapping between net energy balance and net greenhouse gas emissions, though, as the details of how the crops are grown to produce biofuel stocks, the fuels used for a transportation and production processes (i.e. coal vs. natural gas vs. oil), and other considerations can all be important.

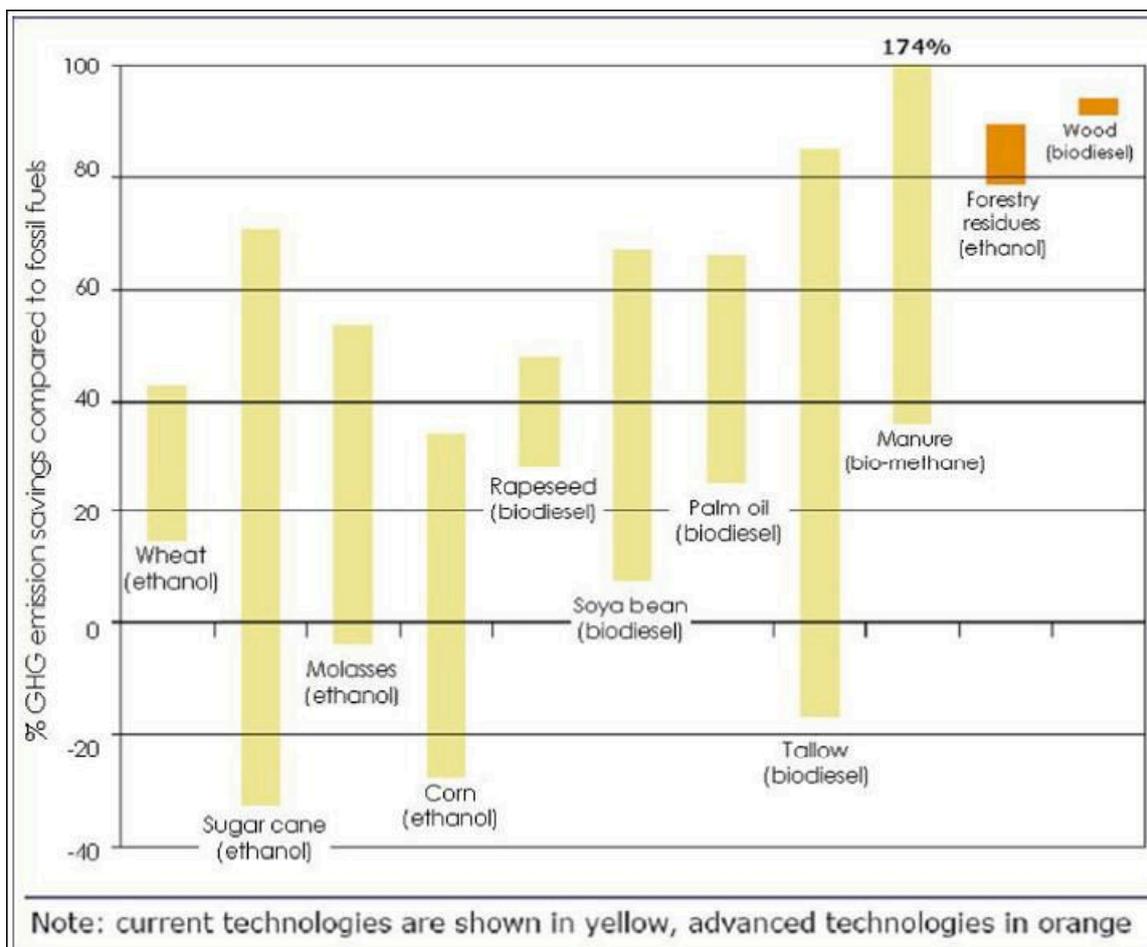
Most recent analyses show a positive benefit on net greenhouse gas emissions from using liquid biofuels, ranging from fairly small for the corn-ethanol system to substantially greater for producing ethanol from sugarcane or biodiesel from palm oil, if peat soil conversion and indirect land-use changes are not considered (Hill et al. 2006; Gallagher 2008;

Searchinger et al. 2008). There is significant variation, though, even for any particular biofuel, due to differences in agricultural practices and in transportation and processing. For example, the Gallagher (2008) report indicates that ethanol produced from corn sometimes can have a negative effect on net greenhouse gas emissions (compared to fossil fuel) of almost 30% but can also have a net positive effect of somewhat over 30% (Figure 1.4); recent estimates for the average net greenhouse gas savings from the corn-ethanol system range from +12% to +20% (Hill et al. 2006; Searchinger et al. 2008). The net greenhouse gas emissions from using cellulosic ethanol are generally considered to be much more positive, particularly if the feedstock comes from wood or from perennial grasses grown on non-agricultural lands (Farrell et al. 2006; Tilman et al. 2006; Gallagher 2008). For sugarcane, the use of bagasse rather than fossil fuels for heat and power results in a significant decrease in the net emissions of greenhouse gases: an average savings in emissions of 2 kg of CO₂ equivalents per liter of ethanol produced for 40 facilities in Brazil using this approach (Macedo et al 2008). However, as mentioned before the GHG savings may be even higher when bagasse is used to produce electricity for public supply and process heat.

The net greenhouse gas emissions associated with producing BtL from wood is estimated as 28% to 90% positive savings, compared to gasoline (Gallagher 2008; Jungbluth et al. 2008). Producing methane gas from manure can have positive savings in net greenhouse gas emissions that range from 40% to over 170% (Gallagher 2008). Net greenhouse gas emissions are discussed further in Chapter 5 (Menichetti and Otto 2009).

Most analyses of the effects of biofuels on net greenhouse gas emissions have focused on CO₂. While CO₂ is the major cause of global

Figure 1.4 Net savings in greenhouse gas emissions from various biofuel technologies, in comparison to fossil fuels. Positive numbers reflect less greenhouse gas emissions than fossil fuels, and negative numbers reflect greater emission. Reprinted from Gallagher (2008).



warming, other gases such as methane (CH_4) and nitrous oxide (N_2O) also contribute to greenhouse warming. Nitrous oxide is a more potent greenhouse gas, one that is almost 300-fold greater in its ability to warm the planet than is CO_2 (for an equivalent mass) over a 100-year average period (Prather et al. 2001). Nitrous oxide is also a major contributor to ozone destruction in the stratosphere, resulting in the creation of “holes” that allow more penetration of UV radiation to the Earth’s

surface. Crutzen et al. (2007) concluded that most lifecycle analyses for biofuels have underestimated the importance of N_2O , generally by 3- to 5-fold, and that increased N_2O fluxes associated with producing biofuels from crops such as corn and rapeseed is likely to more than offset any positive advantage from reduced CO_2 fluxes (compared to fossil fuels). The Crutzen et al. (2007) analysis has been controversial, particularly with regard to their allocation to specific fuel crops. The

Gallagher (2008) report – based on the North Energy (2008) report cited therein – concludes that the findings of Crutzen et al. (2007) may not be robust. Gallagher (2008) nonetheless concedes that most previous studies, including the analysis of the IPCC, may have underestimated the importance of N₂O emissions, and that in “some instances,” full consideration of these emissions will result in shifting the net greenhouse gas emissions of biofuels from positive to negative.

The role of biofuels as a contributor to the N₂O flux clearly deserves further analysis. However, the evidence for an increase in N₂O fluxes to the atmosphere due to human acceleration of the nitrogen cycle is indisputable, and agriculture is the major driver of the change (Galloway et al. 2004). Since pre-industrial times, the N₂O emission rate has increased globally by roughly 50%, a number that is well constrained by historical data on atmospheric concentrations that are preserved in bubbles in glaciers (Prather et al. 2001; Galloway et al. 2004). Nitrous oxide is formed inadvertently as a byproduct of bacterial processing of nitrogen in soils, sediments, and waters. Consequently, while increased use of nitrogen fertilizer is the major driver of the global increase in N₂O fluxes, only some of this moves directly from agricultural fields to the atmosphere. Much of the flux occurs in downstream aquatic ecosystems that receive nitrogen pollution from agricultural fields and from animal wastes (Galloway et al. 2004). Overall, approximately 4% of the nitrogen that human activity introduces into the environment ends up as N₂O in the atmosphere (Prather et al. 2001; Galloway et al. 2004; Crutzen et al. 2007). Many life-cycle analyses have used the IPCC assessment methodology for estimating N₂O fluxes, which tends to give estimates only somewhat over 1% of nitrogen fertilizer use (IPCC 2006). Since biofuel crops often are heavily fertilized with synthetic nitrogen

fertilizer, particularly in industrial countries, biofuel production is clearly contributing to the global N₂O flux. Even in areas not heavily fertilized with nitrogen, which is the case for sugarcane in Brazil, almost 60% of the greenhouse gas emissions not derived from fossil fuel use were due to emissions of N₂O. Most of these are from soil emissions due to the use of fertilizers and industrial effluents like vinasse (the final waste from the fermentation of ethanol from cane) that are used as a fertilizer in the field (Macedo et al. 2008).

A critical consideration for most analyses of net greenhouse gas emissions from biofuels is that they only consider the current level of production and do not address the impacts of land use change that can accompany the expanding use of biofuels. Searchinger et al. (2008) noted that when more agricultural land in the United States is used for growing crops for biofuels, feedbacks through the global economy can tend to result in land conversions – including tropical deforestation – in other nations. These land conversions can have very negative consequences on greenhouse gas emissions, and should be included in the net greenhouse gas balance of the biofuels. In the case of corn-ethanol, Searchinger et al. (2008) conclude that including these indirect land effects doubles the emissions of greenhouse gases compared to burning fossil fuels. Even for making cellulosic ethanol from switchgrass, this analysis shows a large net negative effect on greenhouse gases, if the switchgrass is grown on productive farmland and therefore leads to land conversions elsewhere. Similarly, Fargione et al. (2008) note the large increases in net greenhouse gas emissions that can result from land conversions to grow biofuels. The indirect effects on land use on greenhouse gas emissions are discussed further in Chapter 6 (Ravindranath et al. 2009).

Table 1.2 Comparison of different approaches for addressing global warming from greenhouse gases. Recreated from Heusemann (2008).

Mitigation Strategy	Long-term potential	Stage of Development	Relative cost	Potential risks	Other Issues
Efficiency Improvements					
Supply-side	2-fold improvement	Current tech	Low to med	None	Market imperfections
End-use	>10-fold (?) improvement	R&D	Low to med	None	Market imperfections
Carbon Sequestration					
Terrestrial	~ 200 Gt C	Current tech	low	None	Competition with food, fiber, and fuel wood
Geological					
Coal seams	Several 100 Gt C	R&D, pilot study	Med to high	Environmental health	Leakage, only power plants
Oil & gas fields	Up to 10000 Gt C	R&D, pilot study	Med to high	Environmental health	Leakage, only power plants
Ocean					
CO ₂ disposal	Several 1000 Gt C	R&D, pilot stopped	Med to high	Acidification of marine biota	Public resistance, legality
Iron fertilization	-0.2 Gt C y ⁻¹	R&D, pilot study	Low to med	Marine environment	Public resistance, legality
Carbon intensity reduction					
Decarbonization of fossil fuels	Decarbonize all fossil fuels	Current tech	Low to med	Carbon sequestration -	
Renewable energy					
Biomass	Several-fold increase	Current tech, some R&D	low	Environment, food availability	Land use conflicts
Passive solar	>10-fold increase	Current tech	Very low	None	Market imperfections
Solar thermal	> 10-fold increase	Current tech, some R&D	Low to med	Desert ecosystems	-
Photovoltaics	> 10-fold increase	Current tech, some R&D	Low to med	None or very limited	-
Hydroelectric	No further increase	Current tech, some R&D	Low	Aquatic ecosystems	Public resistance
Wind power	> 10-fold increase	Current tech, some R&D	Low to med	Noise, bird kills	Aesthetics, public resistance
Nuclear	Several fold increase	Current tech, some R&D	Low to med	Radioactivity, catastrophe	Waste proliferation

Growing fuel crops on lands cleared from tropical forests is not only associated with high release of the carbon stocked in the vegetation, but additional and even higher emissions result when former peat bogs are drained (Hooijer et al. 2006). Greenhouse gas emissions from clearing the tropical rainforest in Southeast Asia on mineral soils and wood removal before slash-and-burn were estimated about 600 tons of CO₂-equivalents per hectare (range 300 to 1000). CO₂ emissions from peat soils contribute follow-up emissions of about 90 tons of CO₂-equivalents per hectare and year (range 20 to 270) (Bringezu et al. 2008b, 2009). These emissions may persist for several decades after the clearing, until, with continuous drainage, the carbon stock of the peat will be completely oxidised and released. This is of particular relevance for palm oil plantations in Southeast Asia (Reinhardt et al. 2007). In Indonesia, the government plans to extend the cultivation area for palm oil trees of at least 6 million hectares by a further 20 million hectares (Colchester et al. 2006). Two-thirds of the palm oil expansion to date has depended on destruction of rain forests; the remaining third has converted previously cultivated or fallow land (Grieg-Gran et al. 2007). In the rainforest areas, one quarter of the land is on peat soil. By 2030, a share of 50% from peat soils is expected (Hooijer et al. 2006). If current trends continue, almost 26 million hectares of palm oil would exist in 2030 and the total rainforest area of Indonesia could be reduced by 29% as compared to 2005, and would only cover about half of the original area from 1990 (Bringezu et al. 2008b, 2009).

Concluding thoughts

Although biofuels have a place in an overall global strategy for renewable energy and already supply over 10% of total energy use globally, liquid biofuels supplied only 0.4% of

global energy in 2006. Today as in the past, the use of biofuels is dominated by combustion of solid biofuels such as wood, both in developed and developing nations. Nonetheless, much of the recent emphasis has been on production of liquid biofuels, in part driven by the need to replace crude oil derived fuels in transportation and the desire to reduce CO₂ from the road transport sector. The Gallagher (2008) report, written for the government of the United Kingdom concluded that global liquid biofuel production by 2020 realistically could meet only 2% of the energy needs for roadway vehicle transportation globally, given the constraint of not competing with food production and not causing deforestation. This is far below current targets set by the United Kingdom as well as many other governments, and is in fact about the level of production of ethanol and biodiesel as of 2006 and 2007.

Ethanol as a transportation fuel is not necessarily the most effective strategy for using biofuels to reduce oil imports or greenhouse gas emissions. Other biofuels show greater promise as transportation fuels, including liquid fuels such BtL and gases such as biogas and hydrogen. Since these fuels can be produced from biomass with much greater efficiencies than for ethanol, less land is needed to produce an equivalent amount of energy. Greenhouse gas emissions and other environmental consequences associated with land conversions and intensive agriculture are reduced accordingly, as is the potential competition with food production.

More broadly, the policy of using liquid biofuels directly for transportation may not be the best approach to reduce greenhouse gas emissions or increase energy security. Biofuels can be used far more efficiently in stationary facilities to generate heat or to co-generate heat and electricity than they can as liquid transportation fuels (SRU 2007; Samson et al.

2008; WBGU 2008). When generating heat and electricity, biomass as an energy source can be used almost as efficiently as fossil fuels can. On the other hand, the energetic efficiencies of making liquid fuels are far different for biomass and fossil fuels: converting biomass to a liquid biofuel is only 30% to 40% efficient, while crude oil can be converted to gasoline and diesel with 93% efficiency (De Santi et al. 2008). In a recent study, Samson et al. (2008) report that using switchgrass pellets for heating homes has an energetic efficiency that is 2.7-fold greater than making cellulosic ethanol from switchgrass. As a result, 142 GJ of useful energy can be obtained per hectare of switchgrass grown when used for heating, compared to only 53 GJ per hectare for cellulosic ethanol. The yield of useful energy from corn ethanol is far lower yet, per unit of land needed: only 16 GJ per hectare (Samson et al. 2008). The reduction in greenhouse gas emissions are more than 10-fold greater when using switchgrass for heating than when producing ethanol from corn (Samson et al. 2008).

As noted above, 60% of liquid fossil fuels globally are used in transportation, and 40% are burned in stationary uses (IEA 2008). Consequently, even if biomass is used for stationary energy use rather than liquid transportation fuels, there is a potential to use less crude oil. There is also the potential to instead use less coal; since coal releases more greenhouse gases per unit of useful energy than does crude oil, this offers even greater savings in greenhouse gas emissions. In addition, the co-generation of electricity and heat from biofuels shows great promise and is very efficient (SRU 2007). The resulting electricity can then be used to substitute for electricity from fossil fired power plants, and in the future may also be used to power electric vehicles and plug-in hybrids should these become more prevalent parts of the transportation fleet. The

electricity can also be used to generate hydrogen, which can be stored and used to fuel vehicles that have fuel cells.

No matter how we use biofuels, their capacity as a sustainable energy resource is limited. Many studies conclude that it will not be possible to meet the current mandates set by several governments for liquid biofuels without severe competition for food and environmental degradation, including increased pollution and deforestation (Field et al. 2007; Gallagher 2008; WBGU 2008). Thus, while biofuels can contribute to the energy future of the world, their contribution will never substitute for the current level of use of fossil fuels. The future energy strategy must involve many other approaches, and perhaps most importantly a much greater emphasis on conservation of energy and greater efficiency in energy use, which offer the most cost-effective approaches with the smallest environmental risks and uncertainties (Table 1.2).

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